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An Application of Multiattribute Decision Analysis to the Space Station Freedom Program

Case Study: Automation and Robotics Technology Evaluation

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May 1, 1990

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16. Abstract

This report describes the results of an application of multiattribute analysis to the evaluation of high-leverage prototyping technologies in the automation and robotics (A&R) areas that might contribute to the Space Station (S.S.) Freedom baseline design. An implication of the study is that high-leverage prototyping is beneficial to the S.S. Freedom Program as a means for transferring technology from the advanced development program to the baseline program. The process also highlights the trade-offs to be made between subsidizing high-value, low-risk technology developments versus high-value, high-risk technology developments.

Twenty-one A&R Technology tasks spanning a diverse array of technical concepts were evaluated using multiattribute decision analysis. Because of large uncertainties associated with characterizing the technologies, the methodology was modified to incorporate uncertainty. Eight attributes affected the rankings: initial cost impacts, operations cost impacts, crew productivity, safety, resource requirements, growth potential, and spinoff potential. The four attributes of initial cost impact, operations cost impact, crew productivity and safety affected the rankings the most.

Nine individuals, knowledgeable in Space Station Freedom technologies were interviewed to obtain their preferences.

A questionnaire was sent to the participants to evaluate the process. While the participants had reservations about the manner in which the evaluation was transformed from an informal call for ideas to a full-scale technical evaluation, comments on the usefulness and appropriateness of the methods were positive. Future assessments should consider the development and use of decision support tools to facilitate the process.

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The research described in this publication was carried out by the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration.

ABSTRACT

This report describes the results of an application of multiattribute decision analysis to the evaluation of high-leverage prototyping technologies in the automation and robotics (A&R) areas that might contribute to the Space Station (S.S.) *Freedom* baseline design.

An implication of the study is that high-leverage prototyping is beneficial to the S.S. *Freedom* Program as a means for transferring technology from the advanced development program to the baseline program. The process also highlights the trade-offs to be made between subsidizing high-value, low-risk technology developments versus high-value, high-risk technology developments.

Twenty-one A&R technology tasks spanning a diverse array of technical concepts were evaluated using multiattribute decision analysis. Because of large uncertainties associated with characterizing the technologies, the methodology was modified to incorporate uncertainty. Eight attributes affected the rankings: initial cost impacts, operations cost impacts, crew productivity, safety, resource requirements, growth potential, and spinoff potential. The four attributes of initial cost impact, operations cost impact, crew productivity, and safety affected the rankings the most.

Nine individuals, knowledgeable in Space Station *Freedom* technologies, were successfully interviewed to obtain their preferences. Rankings were calculated for the three groups they represented using forty-eight combinations of assumptions. The three groups were designated Level I, Level II, and third party A&R technology developers.

Analysis showed that the ranking results were consistent across groups and for different model assumptions. The results were also in general agreement with separate evaluations conducted by the three working groups, although a number of the preferred alternatives of the working groups were rated at or near the bottom of the study list.

A questionnaire was sent to the participants to evaluate the process. While the participants had reservations about the manner in which the evaluation was transformed from an informal call for ideas to a full-scale technical evaluation, comments on the usefulness and appropriateness of the methods were positive. Future assessments should consider the development and use of decision support tools to facilitate the process.

FOREWORD

The Automation and Robotics Planning Task was established to provide support for analysis of Space Station *Freedom* automation and robotics (A&R) issues with impacts on baseline implementation. The objectives of the task were to identify a process for A&R implementation, develop an A&R implementation plan, and initiate implementation of the process.

This report describes a methodology for A&R implementation with an application to a specific subset of A&R technologies--high-leverage prototypes. The term "high-leverage" refers to the ability of these technologies to produce large benefits for relatively small investments in research and development funds. The purpose of leveraging is to accelerate the technical readiness of the A&R technologies for inclusion in the S.S. *Freeedom* design.

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SECTION I

INTRODUCTION AND SUMMARY

A. PURPOSE

This publication represents work in support of a Space Station (S.S.) *Freedom* Program process requirement for evaluation and implementation of automation and robotics (A&R) technologies (Reference 1). During 1988, the S.S. *Freedom* Program undertook the development of an A&R implementation plan to provide guidance for assuring that advanced A&R technologies were identified and incorporated into the program. A key element of the plan is a process for evaluating and choosing A&R candidates.

A combination of external factors, program resource constraints, complex management structure, and technological uncertainties results in a complicated design environment for S.S. *Freedom* designers in the selection of A&R candidates. A formalized decision process for A&R candidates can help deal with much of the uncertainty and complexity, while maintaining focus on the ultimate objectives of incorporating A&R into the program. This decision process involves combining A&R technology data with value data (priorities) from S.S. *Freedom* Program management to obtain a ranking of the A&R candidates. The process described herein is based on a technique known as multiattribute decision analysis that has been applied in a number of research and development (R&D) programs to help guide technology research and decision making. This process was modified for application to, and possible adoption by, the S.S. *Freedom* A&R program.

1. Objectives

The purpose of this study is to develop an operational methodology for evaluation of A&R candidates that fulfills a number of objectives (Reference 2). The objectives of the study are to develop a method for the S.S. *Freedom* Program that (1) provides a consistent basis for evaluation; (2) provides a mechanism for reaffirming or checking the analyses of A&R candidate advocates; (3) provides an aggregation of inputs from all concerned parties, based on a consistent set of program evaluation attributes; and (4) provides the program director with a basis for making funding decisions.

An implicit requirement of a method for analyzing A&R candidates is the need to accommodate and quantify uncertainty. A common characteristic of S.S. *Freedom* A&R technology concepts is the lack of precedents. For many of the candidates, there is little, if any, historical data on which to evaluate cost and performance impacts and base estimates of future cost and performance. Consequently, the alternative A&R candidates and their associated data must be represented with probabilistic estimates of their cost and performance. A subobjective of this study was to modify the multiattribute decision analysis methodology to accommodate uncertain (probabilistic) attributes. Technical management requires not only information about A&R candidate value, but also information about the relative uncertainties that stem from incomplete knowledge of the technology and the likelihood that it will perform as required if funded for development. The modifications helped provide a window on the relationship between the mixtures of uncertainty associated with the different A&R candidates and how these uncertainties translate into the final measures of A&R candidate value.

2. Scope

The scope of this study is applied to the evaluation of A&R candidates. While the same process can be used for evaluating non-A&R subsystem elements, the initial application described focuses on A&R because of the complex nature of A&R systems integration. A&R technologies involve interfaces between multiple subsystems and, as such, face a number of implementation barriers. For example, different organizations and contractors are often responsible for different subsystems. Thus, inclusion of A&R elements requires formalized communication between different organizations and mediation of issues by a third party--typically the systems engineering function. In some ways, the study described in this publication is a demonstration of technical feasibility that A&R candidates of high potential value to the S.S. *Freedom* can be identified in a rigorous and credible manner.

The study was applied to a specific class of A&R candidates--high-leverage prototype A&R candidates at a fixed point in time. High-leverage prototypes are technologies with potential to provide substantial S.S. *Freedom* Program benefits for relatively small investments in research and development funds. The invested R&D funding is intended to accelerate the technical development of promising technologies for inclusion in the baseline design. It should be noted that the aim of this publication is to describe the evaluation *process*, the application of multiattribute decision analysis, and illustrate the process with an application. While the study touches upon a number of technical observations regarding the A&R candidates, it does not focus on in-depth technical descriptions. Such descriptions are contained in an unpublished document used as input to the technical assessment process described in Section IV-E. Although the descriptions are not included in this report for proprietary reasons, the assessments of the technical assessors indirectly reflect these descriptions.

3. Safeguards

A common concern of participants in evaluation studies is the ability of the process to withstand artificial manipulation of inputs (data) in order to influence or bias the results to some advantage of a particular proponent (also known as "gaming" the system). This study was no exception. Although safeguards are an implicit objective of any evaluation, the level of concern expressed by some participants indicated that an additional objective was required of the methodology to minimize, by careful monitoring, any opportunities for gaming the process. The safeguards followed are further described in Section IV.

B. BACKGROUND

Background information is necessary to place the evaluation study in context and to present some of the unique factors that complicate the S.S. *Freedom* Program A&R implementation process. The United States Congress has directed the S.S. *Freedom* Program to identify and develop advanced automation and robotics technologies; to provide a Flight Telerobotic Servicer (FTS); and to report on these activities to Congress. The S.S. *Freedom* Program has specified program requirements for the development and accommodation of baseline A&R, and for the provision of hooks and scars for the addition of new candidates, in the Program Requirements Document (PRD) (Reference 1). In addition, the PRD specifically states that baseline applications of A&R (e.g., assignment of specific tasks to the FTS), as well as future applications, are to be based on program-developed criteria that address, at a minimum, the safety, productivity, and life-cycle cost benefits that are to be provided. The PRD also requires the program to develop an A&R implementation plan to address the process of A&R implementation in the program.

"Baselined A&R" in the U.S. S.S. *Freedom* Program currently includes (1) provision of the FTS for assembly, maintenance, and servicing tasks, and (2) knowledge-based fault detection, isolation, and recovery (FDIR) for the Operations Management System (OMS), and for general systems monitoring, diagnosis, redundancy management, test and checkout. In addition to the NASA elements, the international partners have committed to providing the following robotic devices: the Canadian S.S. Remote Manipulator System (SSRMS); the Canadian Special Purpose Dextrous Manipulator (SPDM); the remote manipulator system of the Japanese Experiment Module (JEM-RMS); and the Japanese small fine arm.

The A&R Implementation Plan, currently under development by the S.S. *Freedom* Program Level II, defines the processes, activities, products, and responsibilities for meeting the program A&R requirements for baselined and candidate A&R. The plan demonstrates the program's commitment to evaluating applications for additional A&R candidates, and implementing these candidates where safety, productivity, and life-cycle cost benefits can clearly be provided.

A high-leverage prototyping program as described in section A would be of particular value to the S.S. *Freedom* Program. During the fall of 1988, the S.S. *Freedom* Program at Level II initiated a high-leverage prototyping program via an informal request to the contractor work package centers for high-leverage prototyping concepts. In response to the Level II request, a variety of ideas and concept studies were received through three Level II working groups: the Advanced Automation Working Group (AAWG), the Robotics Working Group (RWG), and the Artificial Intelligence and Expert Systems Technology Working Group (AIESTWG). These ideas and concepts constitute the set of high-leverage prototype A&R candidates to be evaluated. Thus, a need was established for a process and method to evaluate the alternative high-leverage prototype A&R candidates. The process, the methodology, and results of the evaluation are the subject of this report.

C. SUMMARY

The study conclusions and recommendations are summarized below:

1. The Process

(1) The first implication is that high-leverage prototyping is beneficial to the Space Station *Freedom* Program as a means for transferring technology from the advanced development program to the baseline program. Such a mechanism serves as a formal bridge between technology development programs and end-users. The bridge, however, needs to be specified with greater detail.

(2) The purpose of high-leverage prototype A&R candidates is to provide near-term, low-risk A&R applications for inclusion in the baseline S.S. *Freedom*. The interest in low-risk development for this application is to make the application part of the near-term baseline. High risk developments could also be considered if evolutionary applications are included. Any high-leverage prototyping R&D program should determine whether to subsidize high-value, low-risk developments or high-value, high-risk developments. The needs in both cases are different.

(3) The application of multiattribute decision analysis methods was useful for meeting the numerous requirements and constraints specific to the S.S. *Freedom* Program. In particular, the ability of the methodology to address multiple attributes with uncertainty, multiple interested parties to the decision, and monitoring of consensus was seen to be effective and practical.

(4) The process would be facilitated by computer-based interactive programs to enter and edit the evaluation problem to the extent that major steps could be automated. Such a Decision Support System (DSS) for use in a distributed fashion by individuals or as a central display for decision conferencing by a group would allow greater flexibility for examining alternative assumptions. Similar software could also be developed for conducting the argumentation analysis of the technical assessment.

2. The Application

(1) Promising technology areas of potential relevance to the S.S. *Freedom* are:

DIA*	Diagnostic Expert System for electric power and data management
STD	Standards and Tools for Expert Systems
KBS*	Knowledge-based system for fault detection in data management and operations management systems
EXT	Testbed for extended fault-tolerant testing
AUT*	Study of robotics for assembly and fasteners with testbed
FAU*	Knowledge-based system for electric power subsystem fault prediction
MNT*	Study of knowledge-based system development and maintenance tools
ROB*	Software upgrades to demonstration of robotic control of assembly
PRO*	Prototype crew scheduler using advanced search methods

(2) The results of this study are supported by the separate working group evaluations although a number of serious differences were observed. These differences may be attributable to the use of primarily technical criteria as opposed to the Level II S.S. *Freedom* Program criteria outlined in this study.

(3) The majority of recommended high-leverage prototyping A&R candidates involve the study or development of software either for specific applications to systems or to support the software development process in some manner. The high values for software-oriented applications may be a reflection of two world views: (i) high-leverage prototyping should encourage high-risk investments and software developments are perceived as risky; or (ii) high-leverage prototyping should encourage low-risk investments to increase the potential for inclusion in the Baseline S.S. *Freedom* and software developments are perceived as low-risk. It is not clear whether or how these world views might have affected the types of high-leverage prototype A&R candidates at the point of submittal.

(4) The applications of the recommended high-leverage prototyping A&R candidates focus primarily on fault detection, fault tolerance, and fault prediction software using Expert Systems and Knowledge-Based Systems. The target subsystems for these applications are the electric power subsystem, the data management subsystem, and the operations management subsystem.

*Possible overlap with existing work packages and/or with other high-leverage prototyping A&R candidates.

3. The Model Results

(1) The high-leverage prototype A&R candidates examined exhibit high degrees of uncertainty based in part, on schedules and deliverables. Lack of detailed proposal data is likely to have had some, albeit non-quantifiable, effect.

(2) The use of probability distributions is helpful for aggregating and quantifying the magnitude of uncertainties.

(3) The use of argument analysis, although time-consuming, proved useful for expressing the underlying patterns of reasoning for the numerical estimates of the attribute states. The numerical estimates provided a measure of the uncertainty whereas the argument analysis provided a window for the credibility of the estimates. The process used would be aided considerably by a computer-based interactive system.

(4) There is a high degree of concordance (agreement) in the rankings at both the individual and group levels. There is similar robustness under different decision model assumptions. This is due to the comparable weightings assigned to the evaluation attributes by the interested parties interviewed.

4. Recommendations

(1) A high-leverage prototyping program should require the establishment of common goals and perspectives prior to the call for concepts. An element of setting such goals would be the development of program criteria to facilitate the collection of more complete information using a common format.

(2) If a high-leverage prototyping program is initiated, a formal call for proposals should be accompanied by a prescribed set of programmatic A&R evaluation attributes and a common response format, to the extent feasible.

(3) Establish an on-going A&R function at the systems engineering and integration level to support programmatic evaluations and systems engineering trade studies for the S.S. *Freedom* Program. Such a function has never been formally established within the S.S. *Freedom* Program.

(4) Develop and implement a concrete plan for A&R/new technology implementation and incorporation within the S.S. *Freedom* Program and constitute the plan into an operational process.

D. REPORT ORGANIZATION

This report consists of seven sections. Section I introduces the purpose, background, and summary of the study. Section II presents a description of the A&R implementation process. Section III describes the methodology for evaluating A&R candidates in both detail and summary form. Section IV illustrates the methodology with an application to a set of twenty-one high-leverage prototype A&R candidates. Section V presents the results of the application followed by a discussion and the conclusions in Section VI. References are listed in Section VII.

SECTION II

AUTOMATION AND ROBOTICS IMPLEMENTATION

A. A&R IMPLEMENTATION PROCESS

The benefits of automation and robotics to the S.S. *Freedom* Program will come from applications responding to mission and operational needs. A&R technologies based on such needs hold promise for enhancing safety, productivity, and mission success, and reducing life-cycle costs and risks.

An idealized A&R implementation process is shown in Figure 2-1. Requirements are derived from the program objectives, i.e., the mission. Functions to be performed during the design, development, testing, evaluation, assembly, operations, and evolution phases are then derived from the requirements. A first-level screening of the functions is then performed to obtain a list of candidate functions that can be accomplished using A&R technologies. These functions can be described in terms of performance requirements and physical constraints.

The technology base is the source of A&R design candidates. The technology base includes candidates from NASA R&D programs, industry, Department of Defense, and academia. The design candidates can be described in terms of their performance capabilities and physical characteristics. A technical evaluation process matches the appropriate task with the appropriate design candidate or results in task redefinition or refinements in design. This process ultimately results in a set of A&R candidate technologies that are capable of performing particular tasks.

A program-level evaluation then takes place in which the candidates are evaluated according to a set of program-approved criteria. These criteria should include, at a minimum, safety, productivity, life-cycle cost, and technical risk (i.e., maturity), but can include as many others as are warranted (see Section IV). A decision package on the most promising candidates is then prepared for S.S. *Freedom* Program management, which has several options for disposition of the candidates. If the candidate is technologically mature or available off-the-shelf, it can go directly into baseline implementation if funding is allocated. If a candidate has a higher degree of technical risk or technological immaturity, but may have high pay-offs, it is an ideal candidate for a prototyping program. Other candidates may be more suitable for a future growth phase of the S.S. *Freedom* Program, or should be deferred until funding is available.

Some "candidates" are already funded in the baseline (i.e., the FTS). In a case such as this, the evaluation process can be used to identify tasks for the FTS.

B. A&R CANDIDATE DOMAINS

Areas of the program to which A&R technologies can be applied include the broad domains of (1) accommodations and standards for A&R, including design guidelines for the baseline Space Station and hooks and scars for evolution; (2) applications, which includes baseline content, targeted additions to the baseline, high-leverage prototyping of promising candidates, and evolution candidates; and (3) the development environment, which includes testbeds and software development support.

The applications domain refers to the use of A&R technologies for the performance of Space Station tasks in the assembly and operations phases, for both ground and on-orbit systems. Some applications are already funded in the baseline program; other applications may be added as a result of the evaluation process described above.

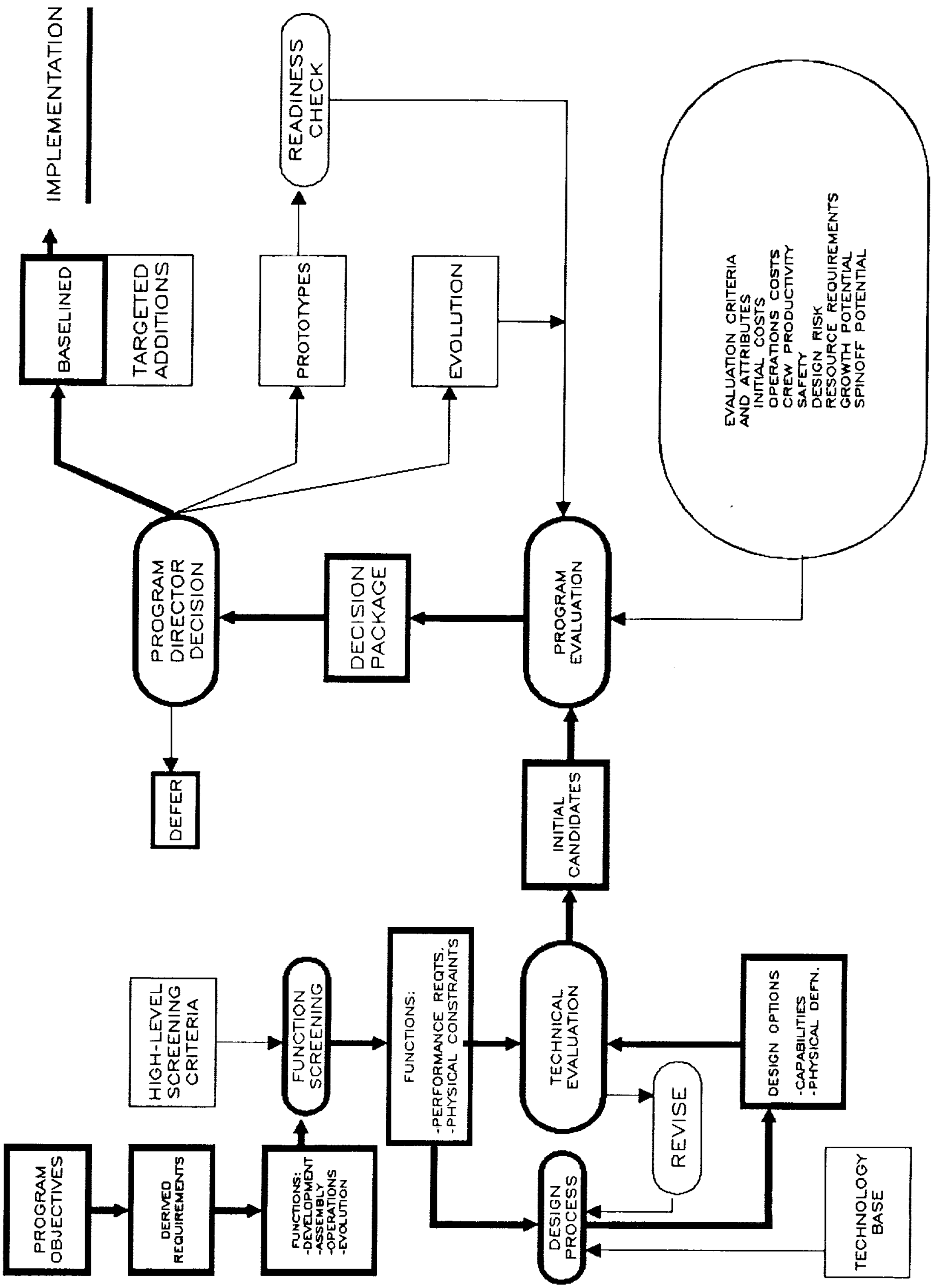


Figure 2-1. A&R Implementation Process

The integration of A&R candidates into the Space Station design must consider (1) design standards for implementation during the design phase to ensure commonality and conformance of design philosophy, and (2) the inclusion of hooks and scars for evolution to enable the Station to accommodate Advanced A&R during the operational phase. The inclusion of hooks and scars for evolution is an activity focused on the period of mature Station operations. The development and monitoring of design standards is an activity focused on the present. The standards must be in place as early in the design process as feasible. Because accommodations and standards span a long project lifetime, the complexity of the systems engineering effort to install such considerations is significant.

The development environment is also an important area for A&R. Development environment technologies are tools that can improve the development, performance, manufacture, and checkout of hardware and software by improving the development environment. These design tools can provide additional safety and level of confidence in station technologies prior to transferring the technologies to the actual ground or space application. Examples include engineering and manufacturing processes, various modeling applications for the design phase, automated testbeds for demonstrating and testing systems and components, design workstations, and software tools for verification and validation of software.

C. A&R EVALUATION CRITERIA

The PRD requires A&R candidates to be evaluated on the basis of safety, productivity, and life-cycle cost benefits. Other benefits to be provided such as growth potential and spinoff to U.S. industry, have been identified by previous studies for the S.S. *Freedom* Program during Phase B (Reference 3). These evaluation criteria formed the basis for development of a hierarchy of objectives and attributes described in Section IV.

SECTION III

METHODOLOGY FOR A&R CANDIDATE EVALUATION

This section describes and illustrates the general methodology used to evaluate and compare alternative A&R candidates. The methodology consists of a number of steps that characterize the alternative A&R candidates, assign utility values to the alternatives, and rank the alternatives based on these utilities.

The general evaluation methodology may be summarized as follows. The process begins with the selection of a set of descriptive but quantifiable attributes designed to characterize each A&R candidate. Values for this set of attributes are then generated for each alternate A&R candidate that specify its response (e.g., cost, performance, safety) under a specific set of assumptions regarding design options and operating environments. (The attributes are discussed in Section IV.) A decision tree can be constructed to relate economic, technological, and environmental uncertainties (i.e., the operating environment) to the cost and performance outcomes (i.e., attribute values) of the alternative A&R candidates. Multiattribute utility functions that reflect the preferences and perceptions of knowledgeable individuals are generated based on interviews with selected personnel. The functions are then employed to generate a multiattribute utility value for each A&R candidate, based on its characteristics under the scenarios reflected within the decision tree. The decision tree is used to compute an expected multiattribute utility value for each alternative A&R candidate, the expected value being taken over the attribute probability distributions. Alternative A&R candidates are ranked according to this expected multiattribute utility value and analyzed for parameter, model, and group sensitivities, risk, and concordance (agreement among rankings).

A. MULTIATTRIBUTE DECISION ANALYSIS

Multiattribute decision analysis is a methodology for providing information to decision makers for comparing and selecting from among complex alternative systems in the presence of uncertainty. The methodology of multiattribute decision analysis is derived from the techniques of operations research, statistics, economics, mathematics, and psychology. Researchers from a wide range of disciplines have participated in the development of multiattribute decision analysis. The first books and papers on the subject appeared in the late 1960s (References 4, 5, 6, 7). The most practical, extensive, and complete presentation of an approach to multiattribute decision analysis is given in the 1976 work of Keeney and Raiffa (Reference 8). Although several approaches to multiattribute decision analysis have been developed (References 9, 10, 11, 12, 13), the method used in this study corresponds to an abbreviated form of that of Keeney and Raiffa. The assumptions needed for the abbreviated form are discussed herein.

Decision problems involving the preference ranking of alternatives, whatever the specific methodology, require two kinds of models (Figure 3-1). One is a "system model" and represents the alternative systems (including any uncertainties) under consideration. The other is a "value model" and represents the preference structure of the decision makers whose preferences are being assessed. The system model describes the alternative systems available to the decision makers in terms of the risk and possible outcomes that could result from each. Risk arises from the uncertainty associated with each alternative and from the uncertain environment in which the alternative exists. The outcomes describe the possible consequences of the alternatives.

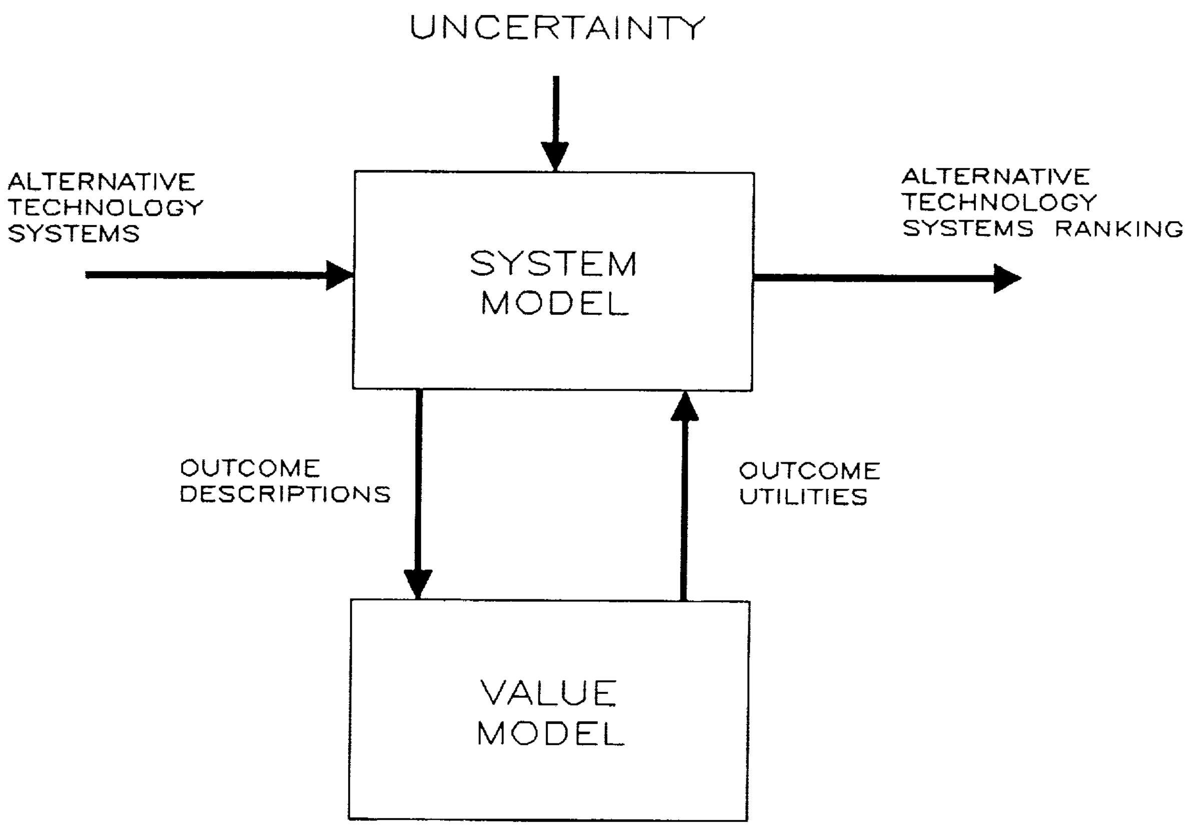


Figure 3-1. Relationship Between System and Value Models

Because of the element of risk, the selection of a specific alternative does not in general guarantee a specific outcome, but rather results in a probabilistic situation in which only one of several outcomes may occur. These outcomes, with their measurable attributes, then form the input to the value model.

The value model prioritizes the outcomes in terms of the preferences of the decision makers for the various outcomes. The measurable attributes of the outcomes are aggregated in a formula (called a multiattribute utility function) whose functional form and parameters are determined by the preference structure of the decision makers. The output of the value model is a multiattribute utility function value for each outcome (outcome utility). These outcome utilities are entered back into the system model where the utility of an alternative can be calculated by taking the expected utility value of the outcomes with each alternative system. These expected utilities for each alternative define a preference ranking over the alternatives, with greater expected utilities being more preferred.

This section describes a procedure for computing the transformation of uncertain alternatives and their attribute states into a probabilistic measure of preference using multiplicative and additive multi-attribute utility functions for the transformation of random variables. Given a model of preference for prioritizing the attribute states, the transformation of random attribute state variables is used to obtain a probabilistic ranking of the alternatives. Thus, not only is the overall expected utility obtained, but also its distribution, mean and variance. A discussion of the multiattribute decision analysis methodology is presented in deterministic form and then extended to the probabilistic form.

1. Decision Trees

Decision trees are used to represent the system model and the inputs to the system model at the gross level required for the decision analysis. Decision trees are graphically depicted by decision nodes (represented by squares), with alternative paths emanating from them and by chance nodes (represented by circles), with probabilistic paths emanating from them. All paths either terminate at another node or terminate at an outcome, which is a description of the consequence of traversing a specific set of paths and nodes through the decison tree from beginning to end. There can be only one originating node (either a decision node or a chance node). There can be many outcomes terminating the decision tree, depending on the complexity of the decision tree.

Figure 3-2 shows a typical decision tree, terminating in 10 outcomes. The symbols "D_i" stand for the i<u>th</u> decision node ("D" for decision). The symbols "P_j" stand for the j<u>th</u> chance node ("P" for probabilistic). The symbols "C_k" stand for the k<u>th</u> outcome ("C" for consequence). Every path emanating from a decision node corresponds to an alternative that the decision makers can select, where "$A_i\ell$" stands for the ℓ<u>th</u> alternative selected at the i<u>th</u> decision node. The decision makers can select one and only one path at each decision node. Every path P_{jm} emanating from a chance node corresponds to one of the uncertain and uncontrollable chance states that can occur at that node, where p_{jm} is the probability that the m<u>th</u> chance state will be realized at the j<u>th</u> chance node. The p_{jm}s must obey the laws of probability theory. Thus, one and only one chance path can be realized from a chance node and the p_{jm}s must sum to 1.0.

The chance nodes and their associated chance paths and probabilities are called "gambles" or "lotteries" in the literature. This report shall refer to them as gambles. An example of a gamble would be a flip of a coin, which could be expected to come up heads 50% of the time and tails 50% of the time.

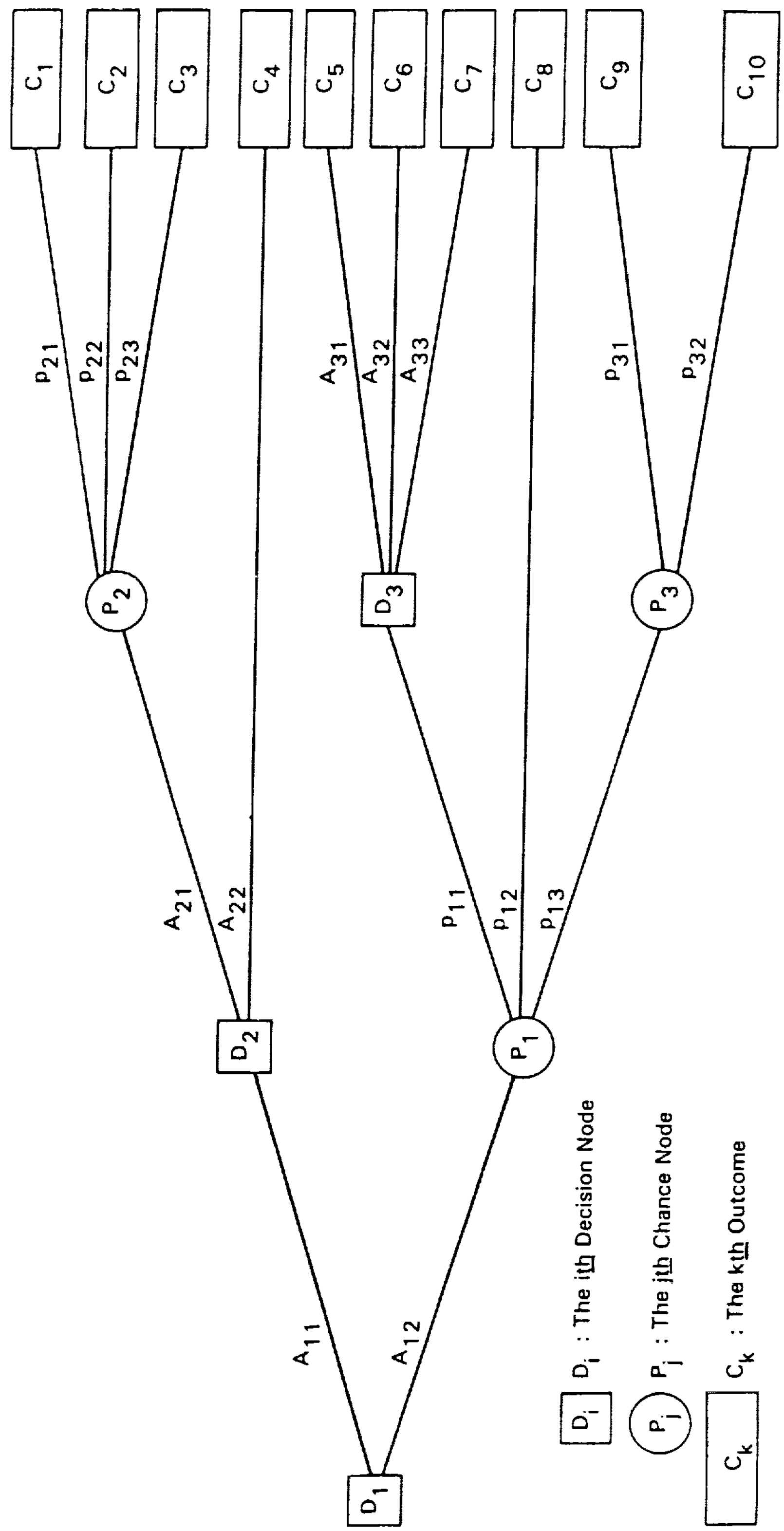


Figure 3-2. Typical Decision Tree

Graphically, such a gamble would be displayed as:

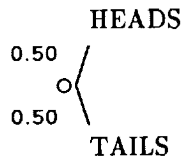


Figure 3-2 has an example of every kind of node-path-outcome relationship. There are examples of decision-node to decision-node paths, decision-node to chance-node paths, decision-node to outcome paths, chance-node to decision-node paths, chance node to chance-node paths, and chance-node to outcome paths.

As an example of how the decision tree might be traversed, imagine that the decision maker selects Alternative Path A_{12} at Decision Node D_1, where he must start. This leads to Chance Node P_1 where Chance Path P_{13} is realized, leading to Chance Node P_3, where Chance Path P_{32} is realized, and terminates with Outcome C_{10}.

2. Determination of Probabilities

The decision trees have probabilities associated with all of the chance paths. These probabilities need to be assessed as perceived by the decision makers or as perceived by experts whose judgment the decision makers would be willing to accept.

Two conditions must be satisfied by the probabilities associated with the chance paths emanating from the single-chance node. The probabilities must be "coherent" and "veridical" (Reference 14). To be "coherent" means that the probabilities obey the laws of probability theory. This requires that the chance paths emanating from a single-chance node correspond to probability events that are mutually exclusive and collectively exhaustive (one and only one of the chance paths must occur), and that the probabilities assigned to all the chance paths emanating from a single-chance node must be non-negative and sum to 1.0. To be "veridical" means that the probabilities must bear some correspondence to reality. For example, if the probability l/n were assigned to the "n" chance paths emanating from a chance node, coherence would be satisfied if the chance paths corresponded to mutually exclusive and collectively exhaustive events because these probabilities sum to 1.0. However, veridicality would be violated if one of the chance paths was perceived as being very improbable, because the assignment of a probability of l/n to that chance path would be inappropriate.

An excellent review and an extensive bibliography on the assessment of probabilities is given in Hogarth (Reference 15). The philosophy and practice used in probability assessment by the Decision Analysis Group at SRI, International is given in Spetzler and Stael Von Holstein (Reference 16). Elementary discussions of probability assessment are given in Brown, Kahr, and Peterson; Keeney and Raiffa; and Schlaifer (see References 14, 8, and 7, respectively) and Winkler (Reference 17). The probability assessment technique presented in this report attempts to satisfy the requirements of coherence and veridicality with a minimum of effort on the part of the assessor and the decision makers or experts whose subjective probabilities are being assessed.

The probability assessment technique first involves the construction of chance paths satisfying the mutually exclusive and collectively exhaustive condition. In Figure 3-2, three chance paths (P_{11}, P_{12}, and P_{13}) emanate from Chance Node P_1. These three chance paths might, for example, correspond to the events: (1) For Chance Path P_{11}, Alternative A&R candidate A_{12} costs $25,000 or less, with a most probable cost of $15,000 and performs as specified; (2) for Chance Path P_{12}, Alternative A&R candidate A_{12} costs more than $12,000 with a most probable cost of $18,000 and performs as specified;

and (3) for Chance Path P_{13}, Alternative A&R candidate A_{12} has a most probable cost of $10,000 but does not perform well enough to be used. Rigorously, according to decision analysis theory, "certainty equivalent" costs (see Reference 8) should be used rather than "most probable" costs as in the preceding statements, but for this discussion "most probable" will suffice.

The next step is to assess probabilities to be assigned to each of the chance paths. This is done by interviewing either the decision makers or their designated experts according to the following format:

(1) Ask the interviewee to rank the chance paths emanating from a chance node in order of decreasing perceived probability of occurrence.

(2) For the chance node, ask the interviewee, "How much more probable is the most-probable chance path than the least-probable chance path? A little? Ten times? A hundred times?"

(3) If the reply is a number, such as "six times more probable," then consider the next least-probable chance path.

(4) If the reply is "a little," then ask, "Is the most-probable chance path 10%, 25%, or 50% more probable?" The interviewee should respond with whatever percentage he feels is appropriate. Then consider the next least-probable chance path.

(5) Repeat (2) to (4) for all of the chance paths of the chance node.

(6) Repeat (1) to (5) for all of the chance nodes relevant to the interview.

This is all the information that is required from the interview for assessing probabilities for the chance paths. The probabilities for the chance paths can be calculated from the interview responses by solving a set of simultaneous equations of the form:

$$p_{jm^*} = x_{jm'} \circ p_{jm'}$$

where "p_{jm^*}" is the probability associated with the most-probable chance path, "p_{jm}" is the probability associated with some other path, and where "$x_{jm'}$" is the response. The p_{jm}s are subject to the condition:

$$\sum_{m=1}^{M} p_{jm} = 1.0$$

In the preceding example, suppose that the responses given were that p_{11} was ten times as probable as p_{13}, but p_{11} was only 25% more probable than p_{12}. The equations to solve would be:

$$p_{11} = 10 \circ p_{13}$$

$$p_{11} = 1.25 \circ p_{12}$$

$$p_{11} + p_{12} + p_{13} = 1.0$$

The solution is:

$$p_{11} = 0.526; \qquad p_{12} = 0.421; \qquad p_{13} = 0.053$$

3. Objectives Hierarchy

The outcomes that terminate the decision tree are to be described in terms of an objectives hierarchy that (1) expresses the preference structure of the decision makers, and (2) is constructed in a manner compatible with the quantification and mathematical conditions required by a multiattribute utility function of the value model. The objectives hierarchy expresses the preference structure of the decision makers in ever increasing detail as one proceeds down through the hierarchy from overall objective to a lower-level hierarchy of sub-objectives. Below the subobjectives are "criteria." The criteria must permit the quantification of performance of the alternatives with respect to the sub-objectives. Associated with each criterion is an "attribute," a quantity that can be measured and for which the decision makers can express preferences for its various states. Figure 3-3 shows an objectives hierarchy with the associated attributes.

The set of attributes must satisfy the following requirements for the value model to be a valid representative of the preference structure of the decision makers:

(1) Completeness: The set of attributes should characterize all of the factors to be considered in the decision-making process.

(2) Comprehensiveness: Each attribute should adequately characterize its associated criterion.

(3) Importance: Each attribute should represent a significant criterion in the decision-making process, at least in the sense that the attribute has the potential for affecting the preference ordering of the alternatives under consideration.

(4) Measurability: Each attribute should be capable of being objectively or subjectively quantified; technically, this requires that it be possible to establish an attribute utility function for each attribute.

(5) Familiarity: Each attribute should be understandable to the decision makers in the sense that they should be able to identify preferences for different states of the attribute for gambles over the states of the attribute.

(6) Nonredundancy: Two attributes should not measure the same criterion, thus resulting in double counting.

(7) Independence: The value model should be so structured that changes within certain limits in the state of one attribute should not affect the preference ordering for states of another attribute or the preference ordering for gambles over the states of another attribute.

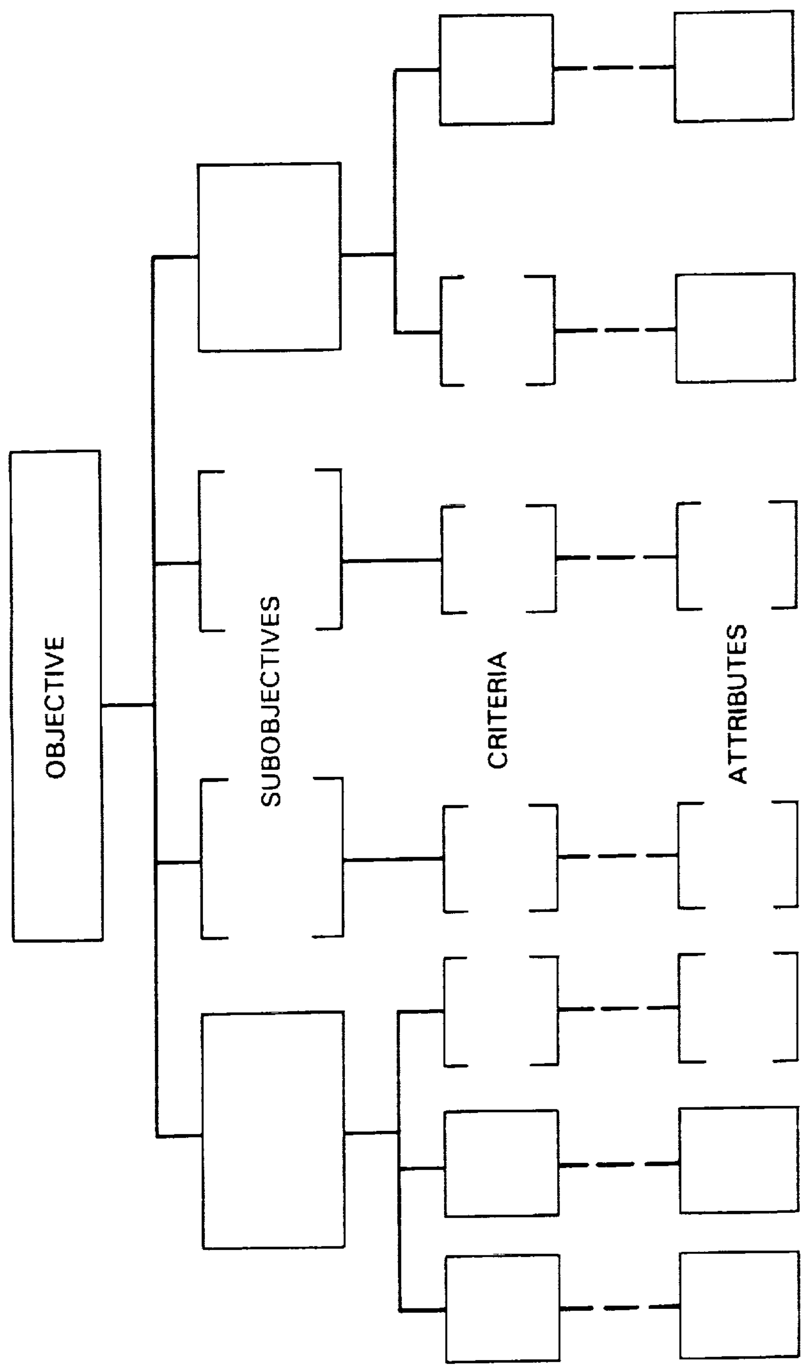


Figure 3-3. Hierarchy of Objectives, Criteria, and Attributes

4. Attribute Utility Functions and the Multiattribute Utility Function

The set of attributes associated with the objectives of a decision analysis must satisfy certain measurability and mathematical requirements. If these requirements are satisfied, then it is possible to formulate a mathematical function, called a multiattribute utility function, that will assign numbers, called outcome utilities, to the set of attribute states characterizing an outcome. The multiattribute utility function used is that of Keeney and Raiffa (see Reference 8). The outcome utilities generated by the Keeney and Raiffa multiattribute utility function have the properties of Von Neumann and Morgenstern utilities (Reference 18), that is:

(1) Greater outcome utility values correspond to more preferred outcomes.
(2) The utility value to be assigned to a gamble is the expected value of the outcome utilities of the gamble.

The mathematical axioms that must be valid for these two properties to hold were first derived by Von Neumann and Morgenstern (Reference 18) and expositions of these axioms are given in a variety of sources (References 19, 20, 21, 22).

To every outcome an N-dimensional vector of attributes $\vec{x} = <x_1,..., x_N>$ will be associated, the set of which satisfy the attribute requirements cited above. Most of the attribute requirements are self-evident. One requirement, that of attribute independence, is a condition that makes it possible to consider preferences between states of a specific attribute, without consideration of the states of the other N-1 attributes. It is thus possible to construct an attribute utility function that is independent of the other attribute states, and which, like the outcome utility function, satisfies the Von Neumann and Morgenstern properties for utility functions. This condition of independence, or some equivalent mathematical condition (see Reference 8 for alternative formulations), is necessary for the Keeney and Raiffa methodology. It is necessary to verify that this condition is valid in practice, or more correctly, to test and identify the bounds of its validity.

To continue the discussion from this point, it is necessary to introduce some mathematical notation:

x_n = The state of the nth attribute.

x_n^o = The least-preferred state to be considered for the nth attribute.

x_n^* = The most-preferred state to be considered for the nth attribute.

$\vec{x}$ = Vector of attribute states characterizing a specific outcome: $\vec{x} = <x_1, x_2, \ldots, x_N>$

$\vec{x}^o$ = An outcome constructed from the least preferred states of all the attributes: $\vec{x}^o = <x_1^o, x_2^o, \ldots, x_N^o>$

$\vec{x}^*$ = An outcome constructed from the most preferred states of all attributes: $\vec{x}^* = <x_1^*, x_2^*, \ldots, x_N^*>$

$\left(x_n, \bar{x}_n^o\right)$ = An outcome in which all attributes except the nth attribute are at their least-preferred state.

$u_n(x_n)$ = The attribute utility of the nth attribute.

$U(\vec{x})$ = The outcome utility of the outcome x (vector of attribute states).

k_n = The attribute scaling constant for the nth attribute: $k_n = u\left(x_n^*, \bar{x}_n^o\right)$

K = The master scaling constant for the multiattribute utility equation. It is an algebraic function of the k_n values.

The mathematics permit the arbitrary assignments:

$u_n(x_n^o) = 0.0$ (least preferred) and $u_n(x_n^*) = 1.0$ (most preferred)

Thus, the attribute utility function values will range from 0.0 to 1.0. Attribute utility function values for attribute states intermediate between the worst and best values are assessed by determining a value of p_n such that the decision makers or their designated experts are indifferent between receiving x_n for sure, or, a gamble that yields x_n^o with probability p_n or x_n^* with probability $1\text{-}p_n$. Graphically, assess p_n, so that:

$$x_n \sim \circ\!\left\langle\begin{array}{ll} p_n & x_n^* \\ 1 - p_n & x_n^o \end{array}\right.$$

where "$\sim$" means indifference. It follows from the mathematics that: $u_n(x_n) = p_n$. This indifference relation is repeated for various attribute states until either a continuous utility function can be approximated or enough discrete points have been assessed for the attribute states under consideration in the analysis.

A similar approach is used to assess the scaling constants (weights). A value for k_n is assessed such that the following indifference holds:

$$\left(x_n^* \ , \ \bar{x}_n^o\right) \sim \circ\!\left\langle\begin{array}{ll} k_n & x^* \\ 1 - k_n & x^o \end{array}\right.$$

<u>The Deterministic Case</u>

The deterministic case refers to the calculation of a single numerical measure for outcome utility that assumes the attribute state values do not represent uncertainty in any way (with a probability distribution). With the assessment of the single-attribute utility functions and attribute scaling constants, the multiattribute utility equation can be solved to yield a deterministic outcome utility value for any outcome under consideration. The multiattribute utility function can be stated in one of two forms. The first form is the multiplicative multiattribute utility function:

$$\text{If, } \sum_{n=1}^{N} k_n \neq 1.0 \text{ , then: } \Rightarrow \ U(\vec{x}) = \frac{1}{K}\left\{\prod_{n=1}^{N}\left[1 + K\cdot k_n \cdot u_n(x_n)\right] - 1\right\} \qquad \text{Eq 1}$$

where the master scaling constant, K, is solved from the equation:

$$1 + K = \prod_{n=1}^{N}\left[1 + K\cdot k_n\right]$$

The second form is the additive multiattribute utility function:

$$\text{If, } \sum_{n=1}^{N} k_n = 1.0 \text{ , then: } \Rightarrow \ U(\vec{x}) = \sum_{n=1}^{N} k_n \cdot u_n(x_n) \qquad \text{Eq 2}$$

The outcome utility function values, like the attribute utility function values, will all range from 0.0 to 1.0 with:

$U_n(\vec{x}^o) = 0.0$ (most preferred)

$U_n(\vec{x}^*) = 1.0$ (least preferred)

Although the mathematical equations appear complex, they can be easily solved, and the information required in the interviews with the decision makers can be minimized. An extended discussion of these equations, their solution, and the assessment of the required data, together with examples taken from actual applications, is given in Keeney and Raiffa (see Reference 8).

The discussion in this section uses an abbreviated form of Keeney and Raiffa's methodology to reduce the interview (questionnaire) time for the interviewee. An assumption is made that utility independence of each attribute implies pair-wise utility independence (i.e., the attributes exhibit utility independence when taken two at a time). This assumption allows the use of Formulation (4) of Theorem 6.2 of Keeney and Raiffa (see Reference 8). Given single-attribute utility independence, it is difficult to construct a realistic example where pair-wise utility independence would be violated.

<u>The Probabilistic Case</u>

The probabilistic case as defined here involves a transformation of random variables where the random variables are the attribute states ($\tilde{x} = \langle\tilde{x}_1, ..., \tilde{x}_N\rangle$), the transformation can either be the additive or multiplicative model, and the result is a cumulative distribution function of the outcome expected utility. Thus a decision maker can view how various levels of uncertainty in the attribute states contribute to the overall uncertainty of each alternative. In fact, depending on the situation, a decision maker may choose an alternative with a lower expected utility--and lower uncertainty over an alternative with a higher expected utility, but with greater uncertainty. This approach enables such a choice.

Because of the non-linear form of the multiplicative model, the analytical transformation of an arbitrary number of attributes is intractable. However, Monte Carlo simulation can be used to effectively compute the transformation. At each trial, a random sample is drawn from the attribute state CDFs (the $\tilde{x}_n$'s). The sequence of these random values, x_α ($\alpha = 1, 2, ..., M$ = number of Monte Carlo trials), is then substituted into the individual attribute utility functions to compute a probabilistic attribute utility value. The $\tilde{u}_n(\tilde{x}_n)$'s) are then used to compute an overall probabilistic expected utility of the alternative, $\tilde{U}(\tilde{x})$ (Figure 3-4).

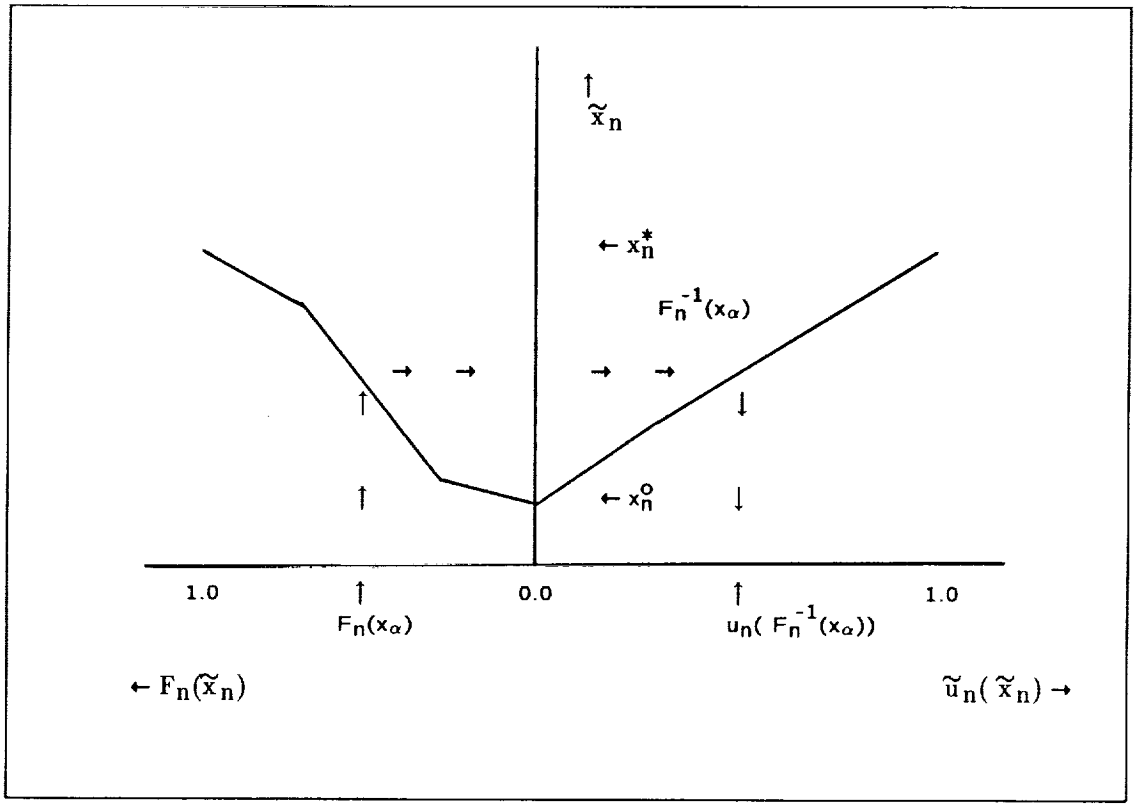


Figure 3-4. Probabilistic Simulation for Attribute, n, and Monte Carlo Trial, α

Formally, the CDF's for the attribute states, $\tilde{x}_n$, are denoted $F_n(\tilde{x}_n)$. Introducing the new notation, the probabilistic mulitiplicative case becomes:

$$\text{If, } \sum_{n=1}^{N} k_n \neq 1.0 \text{ , then: } \Rightarrow \quad \tilde{U}(\tilde{x}) = \frac{1}{K}\left\{ \prod_{n=1}^{N} [\, 1 + K \cdot k_n \cdot \tilde{u}_n(\tilde{x}_n)\,] - 1 \right\} \qquad \text{Eq 3}$$

where the master scaling constant, K, is solved from the equation:

$$1 + K = \prod_{n=1}^{N} [\, 1 + K \cdot k_n \,]$$

and the probabilistic additive multiattribute utility function:

$$\text{If } \sum_{n=1}^{N} k_n = 1.0 \text{ , then: } \Rightarrow \quad \tilde{U}(\tilde{x}) = \sum_{n=1}^{N} k_n \cdot \tilde{u}_n(\tilde{x}_n) \qquad \text{Eq 4}$$

The outcome utility function values, like the attribute utility function values, will range from 0.0 to 1.0 with:

$\widetilde{U}(\widetilde{x}^{o}) = 0.0$ (least preferred)

$\widetilde{U}(\widetilde{x}^{*}) = 1.0$ (most preferred)

A major assumption required to use this technique is that of *probabilistic* independence between the attribute CDF's. Whether or not this condition is met depends on a number of factors. For example, in general the ranges of the attributes are narrower than $0 \rightarrow \infty$ which tends to ease both the probabilistic and preference/utility independence requirements. In any case, this assumption ought to be examined carefully. Note also that the attribute scaling constants, and utility functions are fixed--that is, the preference model is deterministic--the uncertainty in the attribute states (the alternatives) is the only probabilistic quantity. Further work is needed to understand the uncertainties in preference (perceptions of the attribute ranges).

The steps needed prior to ranking the alternatives are: identification of alternatives, definition of the decision via an objectives hierarchy, the quantification of the criteria in terms of measurable attributes with either point estimates or cumulative distribution functions (CDFs), and determination of a multiattribute utility function with attribute utility functions and attribute scaling constants corresponding to the preference structure of the decision makers. The ranking of the alternatives proceeds in one of two ways.

The deterministic case uses the attribute states (if a CDF is present, the attribute state means are used) to compute the multiattribute utility function to calculate outcome utilities for all of the outcomes. Because point estimates are used, this is a one-time calculation for each alternative. The resulting rankings do not reflect consideration of uncertainty, they are deterministic--determined by the single valued attribute states.

The probabilistic case simulates the uncertainty in attribute states by performing a transformation of random variables using the additive or multiplicative decision model (the overall expected utility is the dependent variable and the attributes are the independent random variables). Monte Carlo simulation is used to repeatedly sample from each attribute state CDF and compute a running mean and standard deviation for the distribution of expected utility. The means and standard deviations provide information on how uncertainties in the attribute states are passed through to the rankings.

5. Ranking the Alternative A&R Candidates

The steps needed prior to ranking the alternatives are: the development of a decision tree, the determination of probabilities for the decision of an objectives hierarchy, the quantification of the criteria in terms of measurable attributes, and the determination of a multiattribute utility function with attribute utility functions and attribute scaling constants corresponding to the preference structure of the decision makers. The ranking of the alternative A&R candidates proceeds as follows (Figure 3-5):

(1) Use the multiattribute utility function to calculate outcome utilities for all of the outcomes of the decision tree.

(2) Calculate a utility value to be assigned to all chance nodes by taking the expected utility value of the utilities assigned to the termination of the chance paths of the chance nodes. The chance paths may terminate at outcomes, other chance nodes, decision nodes, or a combination of these.

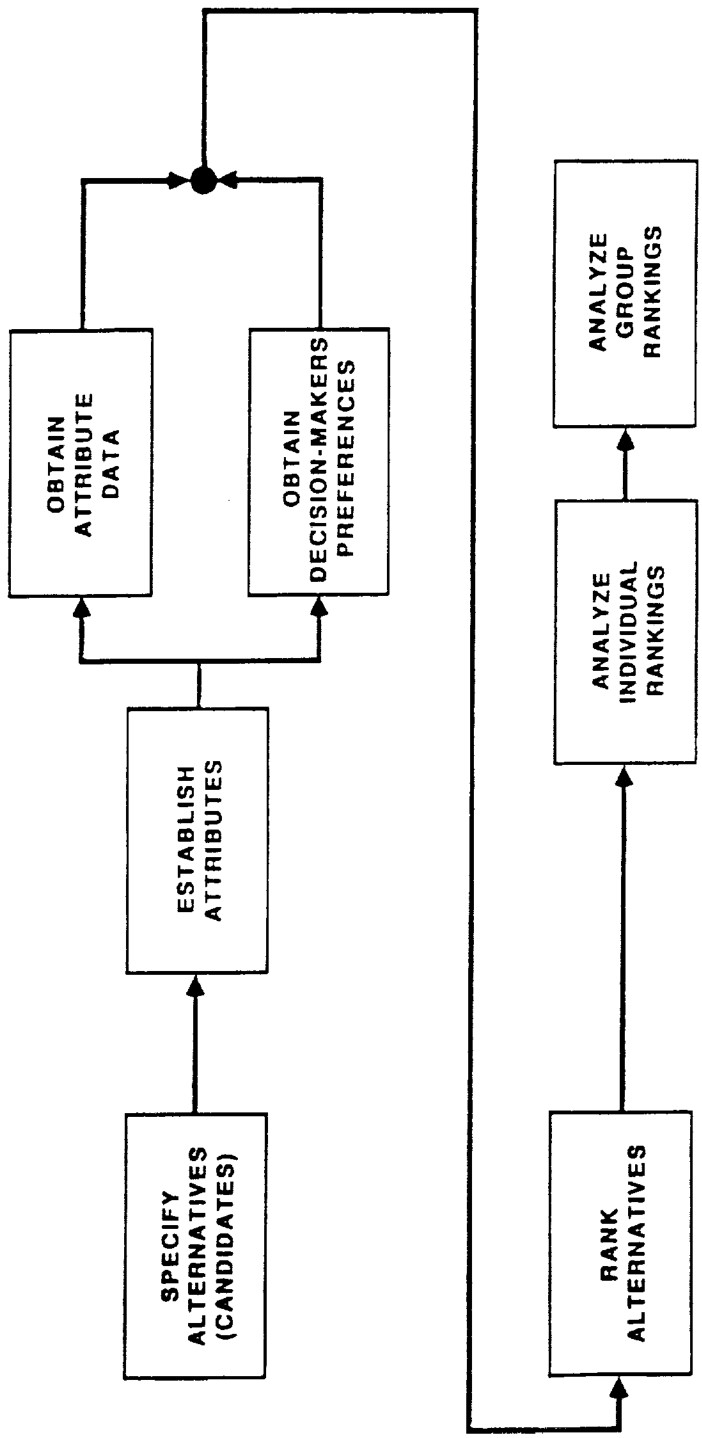


Figure 3-5. Procedure for Ranking Alternatives

(3) Calculate a utility value for all decision nodes by selecting the decision path that terminates in an outcome, chance node, or decision node with the highest utility value. The utility value of that path shall be the utility value assigned to the decision node.

The decision tree for this study has an originating decision node whose decision paths correspond to the alternative A&R candidates under consideration. Steps (1) through (3) are performed by starting with the outcomes shown in Figure 3-2 and assigning utility values to these outcomes. Then Steps (2) and (3) are performed by a "folding back" process, proceeding from right to left, and assigning utility values to the chance nodes and the decision nodes. Finally, utility values are assigned to the decision paths emanating from the originating decision node on the left. These utility values are the ones assigned to the alternative A&R candidates. Because greater utility values correspond to more preferred A&R candidates, a rank order in preference for the alternative A&R candidate can be assigned in correspondence with the utility values. A quantifiable and tangible measure of the strength of preference between the alternative A&R candidates can be obtained by referencing each alternative A&R candidate to a set of A&R candidates where only one attribute, such as initial cost, is varied (References 25 and 26). The differences in the attribute states of this one attribute varied in order to obtain indifference to each of the alterative A&R candidates will provide a tangible measure of the strength of preference between the alternative A&R candidates.

6. Group Decision Models

This section reports on a technique that has proven useful for a number of applications of multiattribute decision analysis involving multiple and disparate groups as stakeholders. The decisions involved similar ranking of technologies for the purposes of further research and development.

This section does not report on techniques involving multiple computer terminals, decision rooms, interactive graphics, and other similar hardware for facilitating the *process*. Rather, this paper describes workable techniques for examining group agreement incorporated into the decision process.

The group decision making approach used here is not new--comparing the judgments of individuals and the resulting rankings has been an area of ongoing study for some time. However, the manner and extent to which these techniques have been used has proven useful in this study.

The approach was developed to examine group preferences in a multiattribute decision making context. When performing a simple (i.e. one group) multiattribute decision analysis, there is the problem of determining whether multiple rankings are in general agreement for the group as a whole. Two general approaches for evaluating group agreement are described: (1) examine the individual rankings directly to deduce agreement; or (2) use the individual rankings to compute a group ranking. An approach to both methods is described here.

In many situations there is no single, isolated, decision maker. When one individual holds the ultimate responsibility for a decision, this person may elect to delegate the decision-making responsibility to a group, or at least consider the preferences of several others prior to making the decision.

Unfortunately, there presently exist no analytical models for group decision making that do not violate some intuitively desirable conditions. Arrow (Reference 23) has demonstrated this fact. Extensive discussions of group decision making can be found in Fishburn (Reference 24), Luce and Raiffa (see Reference 15), and Sen (Reference 25). What can be done is to look at a range of group decision models, and where consensus of the models is found, define that as the consensus of the group (Reference 26).

Three candidate rules considered here are the Rank Sum Rule, the Nash Bargaining Rule, and the Additive Utility Rule.

The Rank Sum Rule requires the calculation of the sum of the ordinal ranks for each alternative, with the alternative receiving the lowest rank sum being most preferred (References 23 and 27).

The Nash Bargaining Rule calculates the product of the utilities assigned by all the individuals to an alternative (Reference 28). The alternatives with the greater utility product are more preferred, and from this a group preference order can be established. The Nash Bargaining Rule satisfies Nash's four axioms of "fairness." As the number of judges increases, the Nash utilities decrease because the individual utilities are ≤ 1. Hence, for even ten decision makers, the Nash utilities are small. Without loss of generality, the Nash utilities can be rescaled by taking the nth root of the product of the individual utilities, where n is the number of decision makers in the group.

The modern formulation of the Additive Utility Rule is that of Harsanyi (Reference 29). The Additive Utility Rule averages the utility values assigned by the individuals to each alternative, with higher average utility values being more preferred.

It should be reemphasized that there is no theoretically compelling reason to use the results of any of these group decision rules, but they do provide information concerning the collective preferences of the decision makers. What is valuable is that techniques are available to test the agreement between the decision rules. That is, while no singular method may suffice for the aggregation of individual preferences, by examining a variety of rules under different assumptions, insights regarding the decision can be viewed in a controlled manner. Smith and Feinberg (Reference 30) have developed a number of guidelines for analysis of group judgments that are used in the present study:

Guideline 1: Combining group judgments and preferences can provide "indicators" of general agreement and whether the group is moving toward or away from general agreement; however, it is not decisive. If two integer ranks are close (indicating possible indifference) but the rankings are reversed, there will be a slight penalty in concordance.

Guideline 2: Studies with identifiable, conflicting groups provide a way to understand the differing world views of the participants'. This is one of the valuable contributions of examining group agreement--discordance initiates a search for these assumptions.

Guideline 3: Always maintain the individual rankings within the analysis; once the results are computed at the group level alone, a degree of freedom is lost and the credibility of the analysis suffers accordingly.

Guideline 4: Groups are often (but not always), defined by institutional or organizational boundaries.

Guideline 5: Always be prepared to explain why the rankings of two groups agree--especially if there is a perceived conflict (corollary: it is generally easier to explain why they disagree). Agreement between dissenting groups can sometimes be attributed to normative versus descriptive behavior (e.g., "safety" is an important factor to everyone until it is discovered that it leads to the same technical conclusion as a competing organization).

Guideline 6: Combining and comparing group judgments is a useful way to search for patterns of agreement in situations with numerous and diverse groups and although it may or may not be used to affect agreement between groups, it provides a tangible measure of progress during the evolution of the project or negotiations.

Again, it should be reemphasized that there is no theoretically compelling reason to use the results of any of these group decision rules, but they do provide information concerning the collective preferences of the decision makers.

B. RISK ANALYSIS

Another element of the sensitivity analysis effort is that of risk analysis. Because of the close connections between the notions of risk and uncertainty, this subsection explains and illustrates the elements of both risk analysis and uncertainty and describes how these concepts are incorporated into the multiattribute decision model and into the sensitivity analysis.

1. Uncertainty and Risk Defined

Definitions of uncertainty and risk typically involve the concept of probability and this commonality often leads to confusion about whether there is any difference. The riskiness of a technology development usually refers the the probability that a technology can actually be produced and the probability of success is an uncertainty. The distinction between uncertainty and risk as used in this study is given below:

Uncertainty is defined as a numerical estimate of probability associated with a random variable, x--in this study, the random variable x is an attribute state variable and the probability is the chance (discrete case) or probability distribution of x occurring. For example, the uncertainty in operations cost could be represented with the statement, "The probability that initial cost for A&R candidate number 3 is greater than $250,000 is 0.90."

Risk is defined as a combination of a probability ***and*** an associated event consequence. In many ways, statements about uncertainty are also statements about risk, however, the notion of risk carries a connotation of "something to be avoided" with it. The "something to be avoided" is the consequence of the event occurring. For example, the risk of an A&R technology could be represented by the statement, "The probability that initial cost for A&R candidate number 3 is greater than $250,000 ***resulting in cancellation of funding*** (the consequence) is 0.90."

Thus, risk and uncertainty are similar, related by their use of probability, but different in that risk subsumes probability. The avoidance of conseqences in risk analysis is often introduced in the context of comparing two alternatives that have equal expected dollar value. An example is the following pair of alternatives:

Option A: $1000 for sure.

Option B: A 50-50 chance of zero dollars or of $2000.

Although both options A and B have equal expected dollar values of $1000, they may not have equal expected utilities for some individuals. An individual's preferences between options A and B reveal his attitude toward risk in the range $0 to $2000:

(1) An individual preferring A to B is characterized as risk-averse.

(2) An individual preferring B to A is characterized as risk-prone.

(3) An individual indifferent between A and B is characterized as risk-neutral.

In the context of A&R candidate evaluation, risk is apparent in the following hypothetical situation:

Option C: Crew productivity savings of 240 EVA hours with an initial cost of $1,000,000.

Option D: A 50-50 chance of saving 180 EVA hours or of 300 EVA hours with an initial cost of $1,000,000.

Both options C and D have equal expected crew productivity savings and equal initial costs but individuals may exhibit different preferences as with the previous dollar example. An individual preferring Option C to Option D is characterized as risk-averse.

Risk attitude implies a certain shape of the individual's utility function and vice versa (see References 5 and 8). A risk-averse attitude for an attribute is equivalent to a concave utility function for that attribute. Also, risk-proneness is equivalent to a convex utility function; and finally, risk-neutrality is equivalent to a linear utility function. All three of these shapes are illustrated in Figure 3-6 for an increasing utility function. An increasing utility function exists for an attribute for which the decision maker prefers higher values to lower values.

The attitude of an individual toward risk varies with the range of outcomes. For example, few of us who would prefer Option B above would give up $1,000,000 for sure for a 50-50 chance at zero or $2,000,000. Nevertheless, variation in individual attitude toward risk is evidenced by many motorists who drive from Los Angeles to Las Vegas to gamble (risk-prone), yet carry collision insurance on their automobiles (risk-averse).

2. Incorporation of Uncertainty in Multiattribute Decision Making

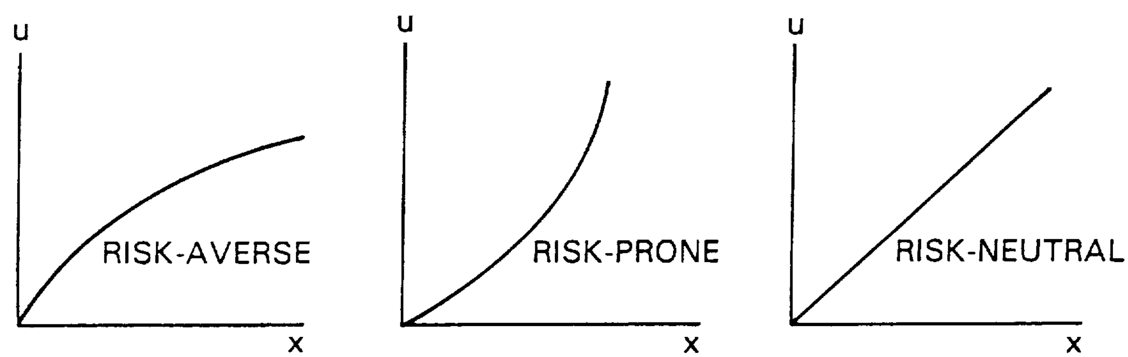
Uncertainty, as used in the context of the study, is generally incorporated in multi-attribute decision making as discrete probability estimates at the chance nodes of the decision tree. The more difficult problem is the case where an attribute may take on any (infinite) number of attribute states over its range.

There may be little doubt that a given A&R candidate will cost $250,000 and so a point estimate is sufficient. However, the same candidate may save between 100 and 200 EVA hours but it is not at all clear what attribute state might actually occur as an outcome due to a host of uncertainties stemming from design choices, operations factors, and unforeseen contingencies (to name a few). Such uncertainties are better represented with probability distributions. The implementation used in this study requires an alternate, but equivalent form of the probability density function, the cumulative distribution function or CDF (Reference 31). The probability distribution contains more information than the point estimate and it is of interest how the varied mixture of attribute state point estimates and probability distributions are combined to derive a probabilistic estimate of multiattribute utility. With such a probabilistic estimate, the variance and standard deviation can be used to explicitly view the level of aggregate uncertainty due to the combined uncertainties in all of the attribute state distributions.

Thus, the technical manager can be presented with a more powerful representation of preference. Rather than presenting only the deterministic multiattribute utilities and forcing the decision maker to accept the A&R candidates rank ordered on the assumption of equal uncertainty among the attribute states, the mean and variance (or in another form, the standard deviation) of each multiattribute utility can be provided. The relative magnitude of the uncertainties can be viewed explicitly to reveal the high-value, low-risk options. For example, comparing a high value, high uncertainty A&R candidate with a lower value, low uncertainty A&R candidate provides a way for the technical manager to select lower value options based on minimizing uncertainty and hence, risk--the risk of selecting the wrong candidate.

3. Incorporation of Risk in Multiattribute Decision Making

Risk has usually been incorporated in multiattribute decision making by taking the individual decision maker's utility functions as probabilities of various outcomes and combining them to obtain an expected multiattribute utility for each decision alternative. Alternatives can then be ranked in order of expected multiattribute utility with the higher expected utility being the more preferred. The incorporation of risk in such a ranking occurs because the individual's attitude toward risk is embodied in the utility functions used to calculate expected utility. If the individual is risk-averse, then his multiattribute utility function will yield lower utility values for riskier alternatives. Similarly, if the individual is risk-prone, riskier alternatives will have higher utility values.



(X ≡ Growth Potential)

Figure 3-6. Examples of Increasing Utility Functions for Different Risk Attitudes

C. CONCORDANCE

It is important to determine the extent of agreement among interviewees as to the ranking of the alternative A&R candidates. The analyst is faced with a set of outcomes as in Figure 3-7. Judges I and II agree on the most important alternatives (A and C) and judges II and III disagree on the most important alternatives. The issue becomes, "Is there any general measure of agreement for the group of three judges (or k judges for that matter)?"

One such measure from the field of rank correlation is a statistic known as Kendall's Coefficient of Concordance (Reference 32). This statistic varies between zero and one, with one corresponding to exact agreement among the judges and lower values indicating a greater degree of disagreement. The statistic has a known probability distribution and so tests of significance can be performed.

The hypothesis that the set of rankings produced by a number of judges is independent is tested. The null hypothesis, if accepted, would imply disagreement among judges. The more decisively one rejects this null hypothesis, the greater is the agreement, or concordance, among the judges.

Kendall's Coefficient of Concordance, W, is given by the following equations:

$$W = \frac{S}{\frac{1}{12} k^2 (N^3 - N) - k \sum_{i=1}^{k} T_i}$$

where

$$S = \sum_{j=1}^{N} \left(R_j - \bar{R}\right)^2$$

$$\bar{R} = \frac{1}{N} \sum_{j=1}^{N} R_j = \frac{k(N+1)}{2}$$

$$T_i = \frac{1}{12} \sum_{j=1}^{N} \left(t_{ij}^3 - t_{ij}\right)$$

and

N = Number of alternatives

k = Number of judges

R_j = Sum of the ranks assigned to alternative j

t_{ij} = Number of tied observations: rank j and judge i[1]

Tables for 5% and 1% significance points are available for selected S values (the unnormalized statistic) and various values of k and N (Reference 33). Note that when $N \geq 7$ the statistic $k(N-1)W$ has (approximately), a chi-square distribution with $N-1$ degrees-of-freedom. Thus, when $k(N-1)W$ exceeds the critical significance point, the null hypothesis of independence of rankings, or lack of concordance among the judges is rejected.

[1]The ranks, Rj, of tied observations are taken as equal to the average of the ranks they would have been assigned had no ties occurred. For example, suppose five alternatives, a through e, are ranked (from best to worst) d, a, c, e, b, with c and e tied. Ranks would be assigned as follows: d-1, a-2, c-3.5, e-3.5, b-5.

RANKINGS FOR EACH ALTERNATIVE, i, BY JUDGE, j

		Judge	
Alternatives	I	II	III
1. A	2	2	1
2. B	3	3	3
3. C	1	1	2
4. D	4	5	5
5. E	5	4	4

Figure 3-7. Sample Rankings for Concordance Analysis

Given a set of N alternatives and their rankings--one for each member of the group, it is now possible to test the hypothesis for agreement or disagreement for the individuals as a group. As will be shown later, this is a straightforward process. The problem still remains that even though the individuals may agree as a group, disagreements may exist between judges over specific alternatives. Before addressing this problem, a second approach for group decision making is described--computing a group ranking from the individual rankings.

D. ARGUMENTATION ANALYSIS

The evaluation and ranking of new technologies is hampered by the lack of quantitative attribute data. High-leverage prototyping A&R candidates are no exception. Because historical data are rare in such cases, the assessment of attribute states is often reduced to educated "guesswork" by individuals. Unfortunately, such procedures may involve a mixture of differing assumptions and reasoning for estimating the attribute states. Although attempts are sometimes made to capture the rationale for an attribute state estimate, the rationale is a weak measure of reliability or grounding because it provides only a limited and somewhat unstructured insight as to the basis or reasoning for the estimate. The high levels of uncertainty in attribute states for unproven A&R candidates requires a more formalized process for understanding the rationale behind each estimate. The following approach used in this study attempts to develop an understanding of the patterns of reasoning underlying the rationale.

Models of attribute state estimates (point estimates or probability estimates) can be viewed as sets of propositions or logical statements (arguments) selected to convince the user that the estimates are credible (Reference 34). Such arguments represent the basis of the model used to derive the estimates. The mode of discourse for situations with very limited or no quantitative information often reverts to a measure of validity based on argumentation. A qualitative framework exists for capturing the structure of complex arguments based on the the work of Toulmin (References 35 and 36). This framework, consisting of subdividing arguments into components, has been used and applied in a number of situations involving unstructured and uncertain environments (References 37, 38, and 39). Argumentation analysis has also been proposed as a way of understanding the underpinnings of attribute state data in multiattribute decision systems (see Reference 39).

Within the Toulmin framework, every argument involves a *claim* (assertion) of truthfulness of a given set of conditions or proposed set of actions. The claim of an argument is usually preceded by the term, "Then ..." or "Therefore ...". To justify a claim, every argument appeals to a body of evidence supporting the claim. Within the Toulmin framework (Figure 3-8), this component is called *data*. The use of data or evidence is typically preceded by the word "Given ...". The license which enables the transition from the data to the claim is called the *warrant*. The use of the warrant in an argument is preceded by the word "Because ...". The warrant and data constitute the major and minor premises of an argument. The *backing* attempts to justify the relevance of a particular set of data to the support of the claim. The backing does not address technical reliability, validity, or objectivity of data (this would involve another argument structure for the data collection procedures). The backing is typically preceded by the term "Since ...". Finally, the *rebuttal* represents any or all challenges to any part of the main argument--against the claim. The rebuttal is typically preceded by the term "Unless ...".

The Toulmin argument framework is applied to identify the argumentation used to support claims about attribute state estimates and expose the underlying plausibility of the attribute state assertion. A form to elicit not only the attribute state, but the underlying arguments is shown in Figure 3-9. The form serves as a basis from which the assumptions, data, and arguments regarding the attribute states are used in the multiattribute decision analysis.

The claim for each attribute state estimate is a numerical response provided by the technical assessor. The form of the numerical response can be a point estimate assigned to the attribute state for a particular high-leverage prototyping A&R candidate (e.g., safety impact = 7.5). Another form of the numerical response can be a CDF assigned to the attribute state that reflects the pattern of uncertainty in the estimate. Still another form of the numerical response is to simply indicate that the attribute state estimate lies somewhere within a range of values but with unknown probability distribution (e.g., the attribute state estimate lies somewhere between 6.2 and 8.5). Another alternative is the complete lack of sufficient information to characterize even the boundaries of the range (e.g., the value lies somewhere between zero and ten but there is no information to indicate where).

The data underlying such claims can be based on the proposed schedule for delivery of products, whether any products are to be delivered, the credibility of the funding level required to perform the task, and other similar "facts" provided in the task description. The warrants for such arguments can be statements such as "the need for the testbed now is based on the objective of delivering the product on an early schedule," or "investment in this task will provide significant operations and maintenance cost savings during the life of the project." The backing reflects a belief in the basic data, for example, "as shown in Report X, there is a clear need to perform this task." The rebuttal simply negates the attribute state estimate; for example, "The estimate is too high because there is insufficient time to build the testbed prototype," or "Any operational savings will be offset by the overhead time required on the ground which was not included in the analysis."

The Toulmin approach is intended to simply identify and organize in a more formal manner the process of estimating and justifying attribute state estimates for the alternatives. The aim is to clarify the reasoning and background of each numerical estimate that is input to the multiattribute decision analysis model. In this manner, not only can the uncertainties inherent to the process be evaluated, but the credibility of the results can be placed in context.

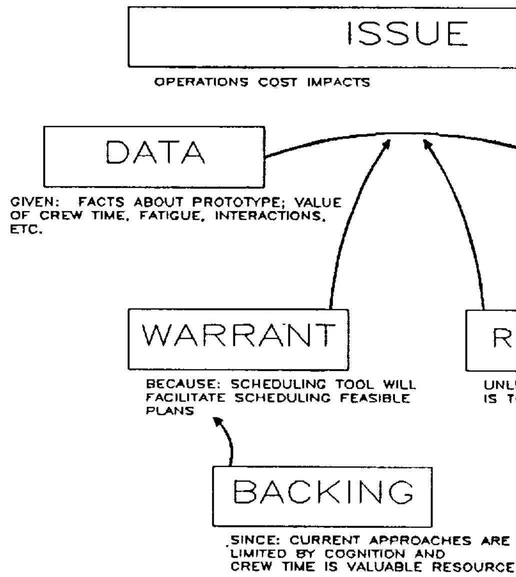


Figure 3-8. Example Toulmin Argument Structure

E. APPROACH SUMMARY

The above approach is summarized by the following stepwise procedure:

(1) Define the alternative A&R candidates. Simultaneously define the objectives hierarchy, decision tree (if applicable), attributes, and attribute scales as required. Identify individuals with an interest in the outcome of the decision to serve as decision making representatives for the relevant interest groups. Revise attributes with interest groups to finalize attribute definitions. Finalize list of A&R candidates.

(2) Obtain attribute state data in either point estimate or cumulative distribution form. CDF's may be obtained directly from other studies or indirectly using subjective probability assessment interviews to elicit the distributions from the participating individuals. Simultaneously, at the point the attribute state is defined, obtain the Toulmin arguments for and against the attribute state assessment.

(3) When all of the attribute state data have been specified, conduct utility assessment interviews with the interested parties participating in the preference assessment to obtain attribute utility functions and trade-off scaling constants.

(4) Collect and organize data from (3) and (4) and perform multiattribute decision analysis computations, sensitivity analysis, and concordance analysis for cases to be studied. Report results and conduct additional analysis as required.

The above steps provide a brief overview of what is, in fact, a detailed and involved process. The next section describes an application of the methodology.

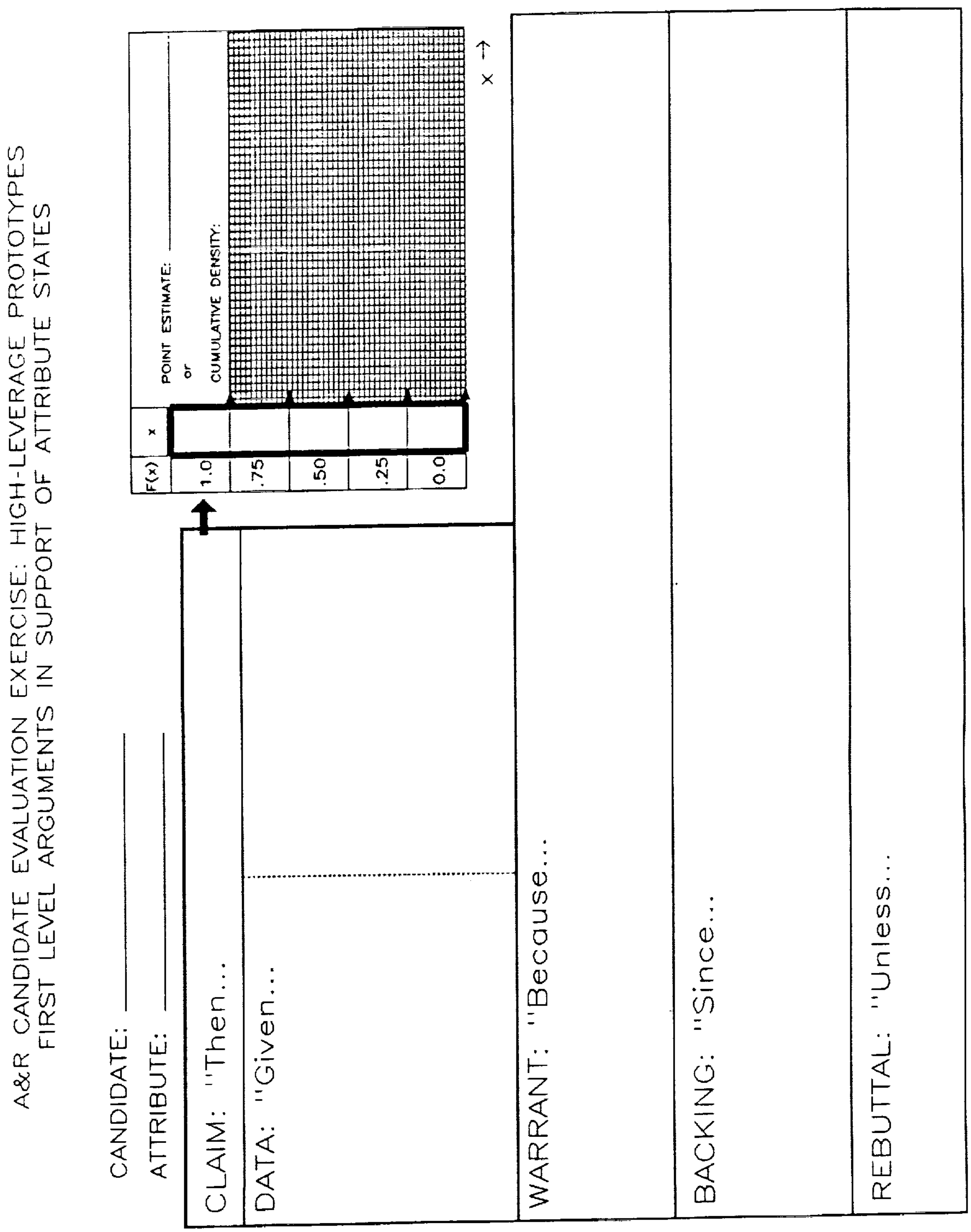


Figure 3-9. Toulmin Argument/Attribute State Data Collection Form

SECTION IV

AN APPLICATION TO HIGH-LEVERAGE PROTOTYPING TECHNOLOGIES

A. OBJECTIVES FOR ASSESSING HIGH-LEVERAGE A&R CANDIDATES

The objectives of the evaluation process are to provide to the Associate Program Director (see Reference 2):

(1) A consistent basis for evaluation (with safeguards).
(2) A mechanism for reaffirming or checking the analysis of the A&R candidate advocates.
(3) An aggregation of input from all concerned parties, based on a consistent set of program evaluation attributes.
(4) An application of a proven tool for the A&R implementation and evaluation process.

The culmination of objectives (1) through (3), an assessment of high-leverage prototyping candidates, is the application under objective (4) described in this section. These objectives can be synthesized into a singular overall goal--apply the methodology to ranking the high-leverage prototyping A&R candidates.

The concept of high-leverage prototyping is to draw on existing R&D efforts by identifying relatively low cost technologies for station implementation that are on the threshold of technical feasibility. Thus by placing small investments in appropriate technologies, the benefits of those technologies can be accelerated. The scope (budget) of the high-leverage prototyping program studied herein is approximately $3 million.

B. DEFINITION OF A&R CANDIDATES

An informal request was distributed in the fall of 1988 via the *ex officio* leaders of the station A&R effort, the leaders of the Advanced Automation Working Group (AAWG), the Robotics Working Group (RWG), and the Artificial Intelligence and Expert Systems Technology Working Group (AIESTWG). From this request, 18 A&R candidate concepts were received and during the course of the following study, the final list grew to 21 A&R candidates as shown in Table 4-1. The A&R candidates comprise a broad mixture of technology developments, hardware and software modifications to existing systems, testbeds, concept studies, issue papers, new applications, and in some cases, simply, new ideas to be examined. The range of costs for the A&R candidates is from $100 thousand to $1.35 million. The final list consisted of 10 candidates from the AAWG, 7 from the RWG, and 4 from the AIESTWG. The AIESTWG submitted fewer concepts because the group had "pre-evaluated" their concepts and were submitting the top candidates from their pre-evaluation.

C. OBJECTIVES, CRITERIA, AND ATTRIBUTES

The hierarchy of objectives, criteria, and attributes for evaluating and ranking high-leverage prototyping A&R candidates is presented in this section. The objectives hierarchy is a structure that

Table 4-1. Alternative High-Leverage Prototyping A&R Candidates

NAME/IDENTIFIER	DESCRIPTION
DIA	Diagnostic Expert System for electric power and data management
STD	Standards and Tools for Expert Systems
KBS	Knowledge-based system for fault detection in data management and operations management systems
EXT	Testbed for extended fault-tolerant testing
PRO	Prototype crew scheduler using advanced search methods
FAU	Knowledge-based system for electric power subsystem fault prediction
ABD	Abductive methodology application/prototype for fault detection
ACC	Accelerated power management and distribution testbed development
ARP	IVA rack-level robotics
VDD	Decision methods application to operations management application
ROB	Software upgrades to demonstration of robotic control of assembly
AUT	Study of robotics for assembly and fasteners with testbed
EVA	Software improvements to EVA Retriever for S.S. *Freedom*
POS	Thermal posture prediction application
SIM	Simulation testbed for robotics analysis
STE	Integrated mobile platform with stereo vision
WOR	World modeling development for S.S. *Freedom* study
ADA	Study of ADA effectiveness for artificial intelligence and expert systems development
MNT	Study of knowledge-based system development and maintenance tools
ES/	Standards for S.S. *Freedom* Knowledge-based operations
KNO	Standards and infrastructure for knowledge acquisition

illustrates the linkage and transition from a broad statement of objectives to specific, measurable attributes that meet the needs of the decision model used to rank the A&R candidates (see Figure 3-3). Included in the hierarchy are an overall objective or goal, subobjectives, criteria, and attributes.

The hierarchy should possess a number of desirable properties. The first and most important property is the hierarchy should lead to an appropriate ranking of alternatives--one that accurately reflects the preferences of the decision makers. The second property of the hierarchy is its clarity and ease of use. Ease of use is critical in order for the ranking to be achieved within time and cost limitations. Some aspects of this ease of use include:

(1) Ease of response for those required to provide preferences for the decision model.

(2) Ease of obtaining attribute data for alternative A&R candidates with regard to the attributes.

(3) Ease of carrying out the sensitivity analysis.

The top level in the hierarchy is an overall statement of the objective for the high-leverage prototyping A&R candidate. The overall objective for the present study is to identify promising high-leverage prototyping A&R candidates.

The subobjectives represent subjects that influence the achievement of the main objective. The subobjectives are chosen to refine the generality of the objective to categorical areas. The suggested categories for the subobjectives include mission, operational, safety, economic, and schedule.

The criteria are derived from requirements and are used to quantify the performance of A&R candidates with respect to their objectives and subobjectives. Criteria are the highest level elements in the hierarchy that are intended to be quantifiable. For example, cost is a logical candidate for the criterion related to the economic subobjective. Thus, under each subobjective there may be one or more criteria.

The high-leverage prototype application criterion for the economic subobjective is to minimize S.S. *Freedom* Program cost impacts. Such impacts are a combination of two factors: initial costs and operations costs. The benefits of a high-leverage prototype are accrued if the operations cost savings exceed the initial or investment cost for development and implementation.

The criterion for the mission subobjective is to maximize productivity. The missions performed by the S.S. *Freedom* can be augmented to different degrees by the high-leverage prototypes and the purpose of this criterion is to seek to maximize the productivity of the crew under such prototypes. Productivity is not simply crew-time per se but rather, implementation of tasks not otherwise performed. The productivity is enhanced when the high-leverage prototytpe A&R candidate accelerates or replaces a task so the crew is available to perform other important work. This is characterized through two elements--productivity enhancement of the crew on-orbit and on the ground.

The criteria for the operational subobjective are to maximize performance of the S.S. *Freedom* and the capability to accommodate new technology upgrades. Maximizing performance refers to the impact of the high-leverage prototype on the overall operational performance of the S.S. *Freedom* which is interpreted here as the effective and efficient utilization of resources to carry out operations. Maximizing accommodations refers to the impact of the high-leverage prototype in facilitating the evolution of the S.S. *Freedom* as new technologies are developed in order to improve the productivity and performance of the system.

The criterion for the safety subobjective is to provide improved safety through design features (e.g., quick system diagnosis) and reductions in extra-vehicular activity (EVA) of the crew. The purpose of this criterion is to account for any contribution of the high-leverage prototype to improved safety as a result of its implementation.

The criterion for the schedule subobjective is to minimize the development time of the high-leverage prototype A&R candidate. Although there are many risks associated with building a system as complex as the S.S. *Freedom*, the focus of this criterion is on development time because the costs of not meeting schedule milestones can be enormous in comparison with early deliveries.

Below the criteria are attributes which measure the extent to which each of the criteria are satisfied. As described in Section III, the list of attributes should meet a number of requirements in order to provide as accurate a representation of each A&R candidate as possible. The attributes developed for this study are based on earlier A&R planning and evaluation activities conducted for the S.S. *Freedom* Program (Reference 40).

The attributes are described in the next section and illustrated in the objectives hierarchy of Figure 4-1. This set includes an overall objective, five subobjectives (economic, mission, operational, safety, and schedule) seven criteria, and eight attributes. The eight attributes selected proved to be manageable within the scope of the study and after the interviews were completed, no significant attribute was found to be missing from the final set chosen.

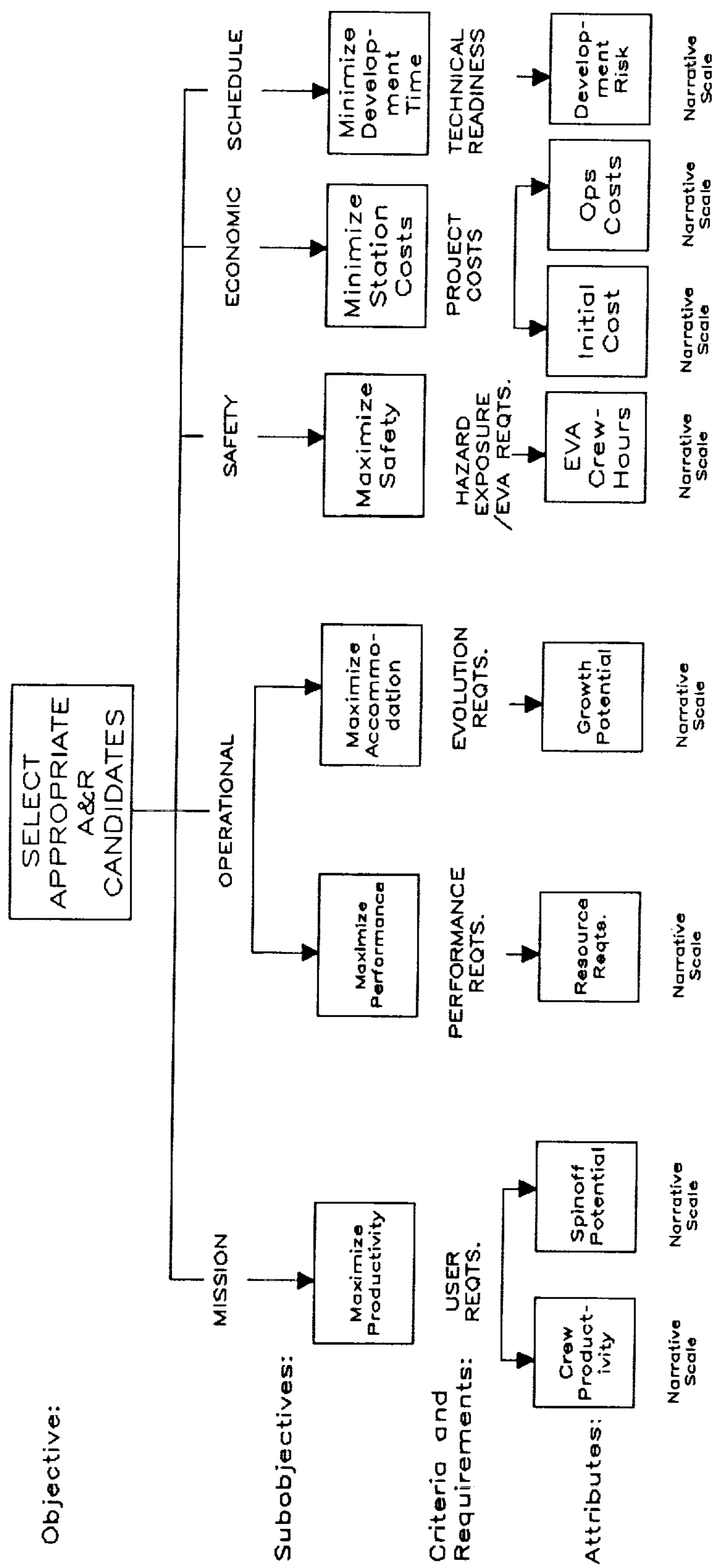


Figure 4-1. Objectives Hierarchy for High-Leverage Prototype Evaluation

D. ATTRIBUTE DEFINITIONS AND SCALES

Because the high-leverage prototyping A&R candidates are being examined in the context of an unbuilt system (the S.S. *Freedom*), obtaining actual measurements of specific economic and operational cost/benefit data is virtually impossible. For this reason, all of the attributes identified in the study require estimates of value. Each attribute is characterized with a narrative scale that relates numerical value on the scale to specific descriptions of corresponding value. The attribute scales are necessary for the decision model to be applied. Each scale requires a unit measure and an upper and lower bound. The upper and lower bounds specify the range of the attribute from a worst case value to a best case value. The upper and lower bounds for each attribute are determined so that all high-leverage prototype A&R candidates considered would fit within these bounds. If an attribute state scale value had fallen outside one of these bounds, the utility of that attribute state could not have been calculated. For this reason, the interviews with interested parties are carried out *after* all the attribute states have been estimated. The attributes and their ranges are summarized in Table 4-2. The attributes are defined below.

Initial cost impacts are defined as potential cost impacts (savings) on Baseline S.S. *Freedom* development (DDT&E) costs (the net S.S. *Freedom* up-front cost change due to funding this high-leverage prototype A&R candidate). For most high-leverage A&R candidates, it is sufficient to limit S.S. *Freedom* net cost impacts to the subsystem in which the A&R candidate resides. Operations cost is defined as potential operations cost (savings) from the expected outcome of funding the high-leverage A&R candidate. Operations cost is estimated at the Station-level if possible, otherwise, it is estimated at the level of the subsystem in which the newly automated function resides. The attribute scales for intial and operations cost are defined in Tables 4-3 and 4-4.

Crew productivity is defined in terms of the potential impact of the high-leverage prototype A&R candidate toward improvement of Station-wide crew time (productivity) by enabling additional productive work. The attribute scale for crew productivity is defined in Table 4-5.

The attribute of safety represents the potential improvement in safety due to better design or reduction in crew hazard exposure. Safety refers generally to (1) a net change in direct crew-time involvement in operations judged potentially hazardous directly to the crew member (such as EVA), or (2) to the Station at large (such as contingency management operations with little margin for response error where a high-speed, high-leverage prototype (e.g., fault diagnosis) could improve safety margins). The attribute scale for safety is defined in Table 4-6.

Development risk represents the likelihood that high-leverage prototyping A&R technologies necessary to automate the function(s) will be available at the required time and within a reasonable margin of presently estimated cost. This attribute is analogous to probability of success although it is not characterized as a formal probability estimate. The attribute scale for development risk is defined in Table 4-7. Note that a higher scale value corresponds to a lower (more preferred) risk.

Resource requirements impacts, a performance subobjective attribute, measure the potential of the product(s) of the high-leverage A&R candidate to mitigate resource constraints such as power and upmass. The attribute scale for resource requirements impact is defined in Table 4-8.

Growth potential represents the net change in the station ability to evolve by accommodating later upgrades due to high-leverage prototyping A&R candidate products. The attribute scale for growth potential is defined in Table 4-9.

Spinoff Potential for Terrestrial Applications characterizes the potential for future commercial application of technologies that is derived from high-leverage A&R candidate-related technologies. The attribute scale for spinoff potential is defined in Table 4-10.

Table 4-2. Attributes and Their Ranges

Attribute	Worst Case	Best Case
Initial Cost Impacts	Candidate provides minimal S.S. *Freedom* benefits at high cost. Significant systems integration costs.	Funding of this candidate will substantially reduce DDT&E and system integration costs for Phase I. Very large net initial cost savings.
Operations Cost Impact	O&M savings likely to be negative; ground O&M savings likely to be neg.; neg. O&M savings on crew training.	Large expected O&M savings by implementing candidate. Savings more than A&R alone, cross-cutting technology savings are likely. Savings extend across lifetime. Large O&M savings due to ground opns and crew training across lifetime.
Crew Productivity	Little or no improvements in crew productivity	Very large improvements in crew productivity are likely if the deliverables are implemented.
Safety	No improvements above minimum reqts. on orbit or ground.	Very large improvements are likely if deliverables are implemented. Adds safety benefits beyond man-in-the-loop due to high-speed computing and/or reduction in EVA activities. Hazards can be mitigated by diagnosis and transition to automated "safe-hold."
Development Risk	Very high risk development; elements at this level not demonstrated; may not be feasible. Requires new testbed concepts.	Virtually no development risk; off-the-shelf technologies, primarily mods. to current system--software, minimal hardware mods.; no testbed facilities; low cost.
Resource Requirements	Could increase power consumption and mass requirements.	Could result in large power and upmass savings.
Growth Potential	Proposal would result in some negative net impacts on S.S. *Freedom* ability to evolve and accept later upgrades.	Proposal would result in a large net improvement in S.S. *Freedom's* ability to accept hooks and scars.
Spinoff Potential	Little, if no terrestrial applications. All developments are S.S. *Freedom*-specific and yield minimal technology transfer. Main sources of transfer are documents describing developments and techniques. Few generalized methods or approaches.	Proposal would have very high level of application to medium and low tech. areas. Technologies will permeate into large markets (e.g., households).

Table 4-3. Attribute Scale for Initial Cost Impacts

Value	Scale Rating	Attribute Description
Best Case	10	Funding of this proposal will substantially reduce DDT&E and system integration costs for the Phase I SSF. Very large net initial cost savings.
	8	This proposal will reduce systems integration costs and potentially reduce DDT&E costs for the Phase I SSF. Initial cost savings from the investment are very likely.
	6	This proposal will have minimal DDT&E cost savings for the Phase I SSF. Impacts are likely during the operations/evolution phase.
	4	Proposal supports SSF assembly but DDT&E costs could be significant.
	2	Proposal supports SSF assembly but DDT&E costs could be large. Some issues for systems integration.
Worst Case	0	Proposal provides minimal SSF benefits at high cost. Significant system integration costs.

Table 4-4. Attribute Scale for Operations Cost Impacts

Value and Scale Rating	On-Orbit Costs Description	Ground Operations Costs Description	Crew Training Costs Description
Best Case 10	Large expected O&M savings due to implementation of proposal deliverables. Savings are more than A&R alone; cross-cutting technology savings are likely. Savings extend across SSF lifetime	Large O&M savings due to proposal are robust--savings impacts will be obtained for grnd ops. across SSF lifetime.	Large O&M savings on costs due to implementation of proposal deliverables are likely.
7	O&M savings are focused within specific subsystems. Savings extend across SSF lifetime.	Significant grnd. O&M savings across SSF lifetime sufficient to break even against DDT&E cost.	Significant O&M savings on training costs.
5	O&M savings are likely and primary savings are expected during the 1st half of the SSF lifetime.	Grnd. O&M savings are sufficient to break even when weighed against initial investment cost (DDT&E). Savings will occur during 1st half of SSF lifetime.	Some O&M savings in crew training costs.
3	O&M savings are expected during the 2nd half of the SSF lifetime.	Grnd. O&M savings are uncertain and likely to occur during the 2nd half of the SSF lifetime.	The crew training benefits for the proposal are uncertain.
0 Worst Case	O&M savings are likely to be negative (no savings).	Grnd. O&M savings are likely to be negative.	Negative O&M savings on crew training costs.

Table 4-5. Attribute Scale for Crew Productivity Impacts

Value	Scale Rating	On-Orbit Productivity Description	Ground Productivity Description
Best Case	10	Very large improvements in crew productivity are likely if the proposal deliverables are implemented.	Large improvements in ground crew productivity are likely.
	7	Significant Improvements in crew productivity are likely.	Significant improvements in ground crew productivity are likely.
	5	Some improvements in crew productivity are likely.	Some improvements in ground crew productivity are likely.
	3	Few improvements in crew productivity are likely if the proposal deliverables are implemented.	Few improvements in ground crew productivity are likely.
Worst Case	0	Little if no improvements in crew productivity are likely.	No improvements in ground crew productivity.

Table 4-6. Attribute Scale for Safety

Value and Scale Rating	On-Orbit Safety Description	Ground Safety Description
Best Case 10	Very large improvements in crew safety are likely if the proposal deliverables are implemented. Adds safety benefits beyond those achievable with man-in-the-loop due to high speed computing and/or reduction in EVA. Hazards can be mitigated by diagnosis and transition of system to automated "safe-hold" mode.	Large improvements in ground safety are likely.
8	Moderate safety improvement is likely. Proposal technologies will increase safety via moderate reductions in required EVA.	Moderate improvements in ground safety are likely.
6	Some improvements in safety. Implementation of proposal deliverables likely to increase safety by preventing improper or ill-defined command sequences from entering the control system. No major effects on EVA activity.	Some improvements in ground safety are likely.
4	Minor improvement in safety. Addition of proposal deliverables increases safety in specific areas by monitoring critical functions and data reduction of SSF status to smaller numbers of parameters. No expected effects on EVA.	Minor improvements in ground safety are likely.
2	Little improvement in safety. Addition of proposal technology may be for reasons other than safety but benefits may be accrued to safety in specific (and perhaps unlikely circumstances). There may be a small increase in required EVA.	Little, if any improvement in ground safety is likely.
0 Worst Case	No improvements in safety above minimum requirements.	No improvements in ground safety above minimum requirements.

Table 4-7. Attribute Scale for Development Risk

Value	Scale Rating	Attribute Description
Best Case	10	Virtually no development risk; off-the-shelf technologies; primarily modifications to the current system--mainly software; minimal hardware modifications; no testbed facilities required; low cost.
	7	Some development risk; testing required for minor interfaces and verification purposes; existing testbeds can be modified and used; software and hardware modifications required; demonstrated feasibility; low level cost uncertainties.
	5	Moderate risk development; some elements may require experiments and ground testing; some new testbed facilities are required; demonstrated feasibility; moderate cost.
	3	High-risk development; numerous elements require ground testing; new testbeds need to be constructed; some in-space testing; feasibility relatively certain.
Worst Case	0	Very high-risk development; elements at this level not demonstrated; may not be feasible. Requires new testbed concepts be constructed.

Table 4-8. Attribute Scale for Resource Requirements Impacts

Value and Scale Rating	Power	Non-Consumables Upmass	Consumables Upmass
Best Case 10	The proposal implementation could result in large power savings.	Large savings in non-consumables is likely.	Large savings in consumables is likely.
8	The proposal could result in significant power savings.	Moderate savings in non-consumables is likely.	Moderate savings in consumables is likely.
6	The proposal could result in some power savings.	Some savings in non-consumables is likely.	Some savings in consumables is likely.
4	The proposal could yield minor savings in power.	Minor savings in non-consumables is possible.	Minor savings in consumables is possible.
2	The proposal would have little impact on power reqts.	Little, if any savings in non-consumables.	Little, if any savings in consumables required.
0 Worst Case	The proposal could increase power consumption.	Could increase non-consumable upmass requirements.	Could increase consumables upmass requirements.

Table 4-9. Attribute Scale for Growth Potential

Value	Scale Rating	Attribute Description
Best Case	10	Proposal would result in a large net improvement in SSF's ability to evolve or accept hooks and scars.
	7	Proposal would result in a moderate net improvement in SSF's ability to evolve or accept later upgrades.
	5	Proposal would result in no net change in SSF's ability to evolve or accept later upgrades.
	3	Proposal would result in minor negative net impacts on SSF's ability to evolve and accept later upgrades.
Worst Case	0	Proposal would result in some negative net impacts on SSF's ability to evolve and accept later upgrades.

Table 4-10. Attribute Scale for Spinoff Potential

Value	Scale Rating	Attribute Description
Best Case	10	Proposal would have very high level of application to medium and low technology areas. Technologies will permeate into large markets (e.g., households).
	7	Proposal would have many applications. Automation activities are applicable to medium technology areas and usable for many areas of manufacturing and production.
	5	Proposal would yield some terrestrial applications. Main terrestrial examples are spinoffs to high technology applications such as computer software and manufacturing.
	3	Few terrestrial applications. Proposal developments are aimed at aerospace and military applications where costs are high and technology-specific (e.g., automated navigation and attitude control). Main terrestrial applications are spinoffs from SSF to other space applications such as unmanned satellites.
Worst Case	0	Little, if no terrestrial applications. All developments are SSF-specific and yield minimal technology transfer. Primary sources for transfer are documents describing developments and techniques. Few generalized methods or approaches to automation and robotics.

E. A&R CANDIDATE ATTRIBUTE STATE DATA

In general, the most difficult step in any evaluation is the collection of data about the alternatives being evaluated--this study was no exception. A variety of data collection procedures were examined in response to critique from the users the evaluation was originally designed to serve--the working group chairmen of the AAWG, RWG, and AIESTWG. The initial approach was to charge the working group leaders with the coordination function of data collection. The list of attributes and scales was to be distributed via the working groups to the authors of the high-leverage prototype A&R candidates who would respond formally through their respective working group.

1. Objections to the Process and Safeguards

Unfortunately, the entire process became embroiled in debate which, coupled with limited working group resources and time resulted in a stalled situation. Although a formal agreement had been made by all involved, at the point where the attributes were being finalized and the collection of attribute data was to begin, a variety of questions was raised to challenge the fairness of the process and its vulnerability to manipulation of input data. The following comment characterizes the argument:

> "*Prior to rating any particular proposal, scale factors must be determined for each attribute. This determination is human-performed and is subject to individual bias and parochial interest. It is a well known fact that mathematics can be creatively utilized to prove just about anything. Therefore, if one were to know the equation applied, one would be able to produce any parochial result desired. Thus, the evaluation process can be easily short-circuited and defeated. Even without specific knowledge of the mechanics of the equation, most of us are well enough imbued with the process to create desired results. ... In short, I think that there are important flaws in the strawman, both as currently configured, and with its use as a decision-making aide. I hope this is the constructive input to your activity which you are seeking* (Reference 41)."

This comment raises two issues. The first issue is the problem of bias or gaming the inputs in such a manner as to gain advantage in the ratings. A number of safeguards minimize the potential for such effects.

The first, and most important safeguard is the performance of the evaluation process by a third party with no stake in the outcome of the selections.

The second safeguard is the assignment of attribute ratings by a third party. Allowing the proposers to assign the attribute data may have been the primary concern here. An additional, related safeguard is the development of arguments and counterarguments to support the attribute state data assignments. The ability to include uncertainty addresses concerns about the subjective nature of the estimates to a degree. If the uncertainties are large, the analysis should reveal and quantify this.

The third safeguard is the separation of the attribute rating and attribute prioritization processes. A different group of individuals assigned the attribute state values from the group of interviewees who provided the attribute utility functions and trade-off scaling constants. In addition, the interviewees providing the priorities (weighting factors) were not presented with any information that would allow them to associate any attribute states with specific high-leverage prototytpe A&R candidates.

The fourth safeguard is the involvement of multiple decision makers across different organizational groups to help assure a balanced view of the process.

The second issue raised by the above comment is the relevance of the attributes to the high-leverage prototype A&R candidates under consideration. It is not clear the list of attributes in some way penalizes different classes of high-leverage prototype A&R candidates because hooks and scars candidates should show benefits under growth potential, while the design tools, standards, and architecture candidates should show benefits under a number of attributes such as initial cost, development risk, and spinoff potential.

As these issues were addressed, it became increasingly apparent that involving the working group leaders to provide attribute state ratings was not workable from their positions as Level II agents and as advocates for high-leverage prototype A&R candidates within their respective working groups. Thus, it became clear the attribute state data could not be expected from (1) the authors of the high-leverage prototype A&R candidates because of concerns over biasing of inputs, (2) the working group chairmen because of their representation of their working groups, or (3) the systems engineering and integration function due to limited resources for A&R support. The next section describes a technical assessment group formed to support the assignment of attribute state values.

2. Technical Assessment Committee

To achieve the objectives of the study, a third-party group was formed to assess the attribute states for each high-leverage prototype A&R candidate. Five individuals participated from the Jet Propulsion Laboratory staff--an organization with the ability to understand the technology alternatives, but no direct interest in the selection of any high-leverage prototyping A&R candidates. Two meetings were held to (1) establish a set of ground rules for the assessment, and (2) review the ground rules after performing a first round exercise to estimate the attribute states to identify any common problems.

3. Ground Rules and Procedure

A major difficulty facing the technical assessment committee was the lack of detailed data on not only the attribute states, but the high-leverage prototype A&R candidate itself. The variation in quality of information varied from extensive 15-page descriptions to one-page summaries. Fortunately, a number of the technical assessment committee members were involved in working group meetings where the authors of the high-leverage prototype A&R candidates described each concept in greater detail. No contacts were made with these authors in order to maintain fairness and reduce bias to the extent possible.

At the first meeting of the technical assessment committee, a compilation of the latest data for each high-leverage prototype A&R candidate was distributed to each member. A discussion of the requirements and purpose of the group was followed by the development of a set of ground rules to be used as guidelines for estimating the attribute states. It was recognized by all that high levels of uncertainty would be systemic to the process and the guidelines were established to facilitate what was viewed as a difficult, but not futile task. The ground rules were:

(1) Any reference to the S.S. *Freedom* is assumed to include space operations and ground operations.

(2) The high-leverage prototype A&R candidate must contribute in a high-leverage context. (i.e., the concept must perform an enabling or a support function (less desirable)).

(3) The high-leverage prototype A&R candidate must have a demonstrable product. There must be specific hardware, software, concepts, methodology, application, or a study of issues delivered.

(4) There should be sufficient information for evaluation and extrapolation of attribute states.

(5) Consideration will be given to the latest, most detailed information.

(6) Give the benefit of doubt to deliverables promised and schedule proposed unless the supporting arguments for these are weak or it is known otherwise that they are unachievable.

(7) The growth potential attribute ratings are aimed at S.S. *Freedom* accommodations as opposed to growth of the high-leverage prototype A&R candidate.

(8) It is assumed that any successor tasks described would be funded through to completion.

After the ground rules were established, subsets of the attributes were assigned to each member of the group. Thus, each individual was responsible for all the attribute states for two attributes across all the high-leverage prototype A&R candidates rather than assessment of all the attributes for a selected number of candidates. Because of large uncertainties in the study, estimates of attribute states could take a number of forms from a total lack of knowledge about the attribute value to a "best guess" estimate.

The most uncertain form of attribute state can be represented with a uniform probability distribution over the attribute range. The uniform distribution, in effect, allows the attribute state to take on any value over the attribute range with equal probability. Because the attribute range is from zero to ten, such a distribution simply indicates the "true" value of the attribute state is somewhere between zero and ten and no more.

Another form of the same distribution which adds some additional information is the uniform distribution over a smaller range than zero to ten. For example, if an attribute state is uniformly distributed between two and four, although it could be anywhere between two and four with equal probability, the range has been reduced from 0-10 to 2-4 which narrows uncertainty about the location of the true estimate to a more specific region of the scale.

A third form of distribution which again narrows the location of the attribute state estimate is the assignment of a non-uniform probability distribution. Within this study, such distributions are obtained using subjective probability assessment interviews to elicit the probability distribution.

Finally, if the attribute state estimates are known with certainty or believed to be distributed with equal uncertainty across all the estimates, the average or mean value can be used. These values (often called "best guess" estimates) are point estimates that provide no quantifiable information about underlying uncertainties.

The implications of the above forms were explained to the technical assessment committee and a series of blank attribute state forms were distributed (see Figure 3-9). The task was clear--the attribute state estimates were needed for 168 attribute states (eight attributes for each of twenty-one high-leverage prototype A&R candidates). Each attribute state (distribution or point estimate) was estimated and the argument(s) for and against the estimate were documented to provide the reasoning process.

4. Sample Questions

The technical assessors were given blank forms on which to provide the attribute state estimates in a number of forms (see Figure 3-9):

(1) The point estimate can be provided directly.

(2) The cumulative distribution function can be specified numerically by providing the 0, 25th, 50th, 75th, and 100th percentiles.

(3) The cumulative distribution function can be specified graphically by sketching the form of the function.

(4) The cumulative distribution function can be elicited using subjective probability assessment techniques to obtain an estimate of the technical assessors uncertainty surrounding the attribute state estimate.

Figure 4-2 illustrates an example of one of these completed forms. At the completion of this activity, the attribute state data were reviewed by the committee. The results are reported in the next section.

5. Attribute State Data

The final database of 168 attribute states is summarized in Figure 4-3 showing the distribution values as a mean and standard deviation and the point estimate values as a single number. Sixty-nine percent (69%) of the 168 attribute states are characterized by cumulative distribution functions (116 attribute states) and thirty-one percent (31%) of the attribute states are point estimates (52 attribute states).

An indication of the level of uncertainty is provided by the fact that fifty-seven percent (57%) of the attribute states are represented by some form of uniform cumulative distribution function (66 attribute states). Five percent (5%) of the attribute states were full-scale uniform distributions where no further judgment could be made regarding resource requirements impacts, growth, and spinoff potential (6 attribute states). The next section describes how the attribute states were used in the interview process to obtain the utility functions and trade-off constants from the interested parties.

F. INTERVIEWS TO OBTAIN PREFERENCES FROM INTERESTED PARTIES

The purpose of the interviews is to obtain the quantified preferences of the interested parties in order to rank alternative high-leverage prototype A&R candidates with the decision model. Equally important is the provision of a formalized process to enable different stakeholders in the decision process to provide input about their preferences. The preference information required from each interested party includes a utility function and a trade-off scaling constant for each attribute. The utility functions characterize how the interested party prefers different levels of an attribute while the trade-off scaling constants characterize how the interested party values one attribute versus the other attributes. Interviewees were sought who were knowledgeable about automation and robotics issues as they pertain to the Space Station Program, and, who were regarded as decision makers within their organizations.

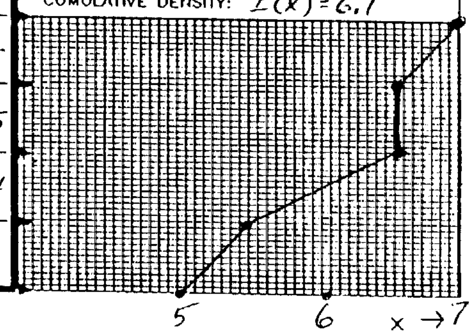
A&R CANDIDATE EVALUATION EXERCISE: HIGH-LEVERAGE PROTOTYPES
FIRST LEVEL ARGUMENTS IN SUPPORT OF ATTRIBUTE STATES

CANDIDATE: AA-2 - PROTOTYPE CREW SCHEDULER

ATTRIBUTE: OPERATIONS COST

F(x)	x
1.0	7
.75	6.5
.50	6.5
.25	5.4
0.0	5

POINT ESTIMATE:
or
CUMULATIVE DENSITY: $E(x) = 6.1$



CLAIM: "Then... O&M Savings likely to extend across life-time

DATA: "Given...
- Value of crewTime - an Ops cost
- fatigue (physical + mental)
- interactions, priorities & uncert.
should allow:
  - flexibility of expression
  - human dimension
  - efficiency
  - generalizability

- Classical Ops Analysis Tools
- New AI methods

WARRANT: "Because...
1. Our aim is to please, not optimize (satisficing solns.); the latitude of heuristics makes such a Tool technically feasible and the Tool is S/W based so the costs are limited.
2. We have an advanced scheduling technology & emerging AI technology -- we can synthesize these into a common tool to save money on high-cost ops items (EVA, fatigue, etc).

BACKING: "Since... 1. The current scheduling process is limited by human cognition, Tools are needed to facilitate the process.
2. "Time is money.

REBUTTAL: "Unless... 1. Crew scheduling at this level is too dynamic for scheduling models (eg, spend more time entering data than producing useful schedules).
2. Crew scheduling is too dangerous w/out ground committee approval.

Figure 4-2. Example Attribute State Data

HIGH-LEVERAGE PROTOTYPE EVALUATION ATTRIBUTE DATA

	DIA	STD	KBS	EXT	PRO	FAU	ABD	ACC	ARP	VDD	ROB	AUT	EVA	POS	SIM	STE	WOR	ADA	MNT	EX/	KNO
INITIAL COST	6	9	8.5 ±.29	7	5	6	4	4	2	5	7	7	4	6 ±.58	4.5 ±.29	3	6	8	6	6.5 ±.29	8
OPERATIONS COST	8.15 ±.73	5.15 ±1.09	6.65 ±.73	4.325 ±.60	6.1 ±.62	4.25 ±.80	3 ±.58	3.3 ±.94	3.9	4.9 ±.85	4.14 ±.39	3.625 ±.22	4.85 ±.76	6 ±.58	4.05 ±.44	5.18 ±.71	3.31 ±.77	5.4 ±.95	4.05 ±.54	2.7 ±1.11	3.92 ±.65
CREW PRODUCTIVITY	5.5 ±.29	5.5 ±.29	6	4.5 ±.29	7.5 ±.29	5	5	3	9.5 ±.29	4.5 ±.29	7	4	4.5 ±.29	3	5	0	5	5	5	5	5
SAFETY	5.2 ±1.33	5.55 ±1.59	.05 ±1.65	5.025 ±1.63	3.325 ±1.58	5.8 ±1.35	5	2.475 ±1.13	2 ±1.07	3.2 ±1.41	4.13 ±1.31	6.28 ±1.59	2.58 ±1.45	2 ±.54	1.98 ±1.1	5.03 ±1.63	2.1 ±1.25	5.03 ±1.63	5.6 ±1.61	5.5 ±2.18	5.55 ±1.59
DEVELOPMENT RISK	6	8	4	8	5	5	3	8	1	2	8	9	5	8	4	5	0	6 ±.58	10	4	0
RESOURCE REQTS.	5.925 ±.40	5 ±.58	4.5 ±.29	6.075 ±.50	4 ±.58	6.4 ±.84	3.5 ±.29	4.92 ±.48	5.13 ±1.04	2.4 ±.50	5.1 ±.34	4.5 ±.29	5.53 ±.65	4.5 ±.29	4.025 ±.29	5.19 ±.43	1.91 ±.55	5 ±.58	5 ±.58	5 ±.58	5 ±.58
GROWTH POTENTIAL	8.5 ±.87	7 ±1.15	7 ±1.15	5 ±2.9	7 ±.58	7 ±.58	7.5 ±1.44	7 ±.58	2.5 ±1.44	5 ±2.9	6.5 ±.65	6.5 ±.65	7 ±1.15	6 ±.58	8 ±.58	7.5 ±.87	5 ±2.89	5 ±1.16	5 ±.29	6.5 ±.87	6 ±.58
SPINOFF POTENTIAL	6 ±.58	1.5 ±.87	6 ±.58	5 ±.29	7.5 ±.87	1.5 ±.87	6 ±1.15	1.87 ±1.65	1.5 ±1.32	1.5 ±.87	1.5 ±1.32	1 ±1.3	7 ±1.15	1.125 ±.99	4 ±.58	7 ±.115	5 ±.29	6 ±.58	1.5 ±.87	1.5 ±.87	1.5 ±.87

Figure 4-3. Attribute State Data For High-Leverage Prototype A&R Candidates

1. Interviewees

The interviewees were persons who would either have a direct role in the development of the high-leverage prototype A&R candidates or who act as advisors in the decision-making process. Representatives were sought from three organizations:

(1) NASA Headquarters (Level I) representatives with a NASA programmatic perspective.

(2) NASA Space Station Program (Level II) representatives with a Space Station Program perspective.

(3) NASA Third Party Technology Program representatives with an A&R technology perspective.

A total of nine individuals were interviewed composed of three from each group between April 17, 1989 and April 28, 1989. Three of the interviewees are technology program managers, two are working group leaders, three are A&R technologists, and one was directly involved in the S.S. *Freedom* operations area. While other groups might have been interviewed (such as contractors or user payload representatives), this group comprises a significant cross-section of interested parties concerned with the high-leverage prototytpe A&R candidates.

The representation of members in the sample was constituted from an initial survey of representatives derived from meeting agendas, personal contacts, and referrals. While this sampling approach is not a random one, there were a number of individuals who simply had to be included because they had played a key role in some aspect of advanced A&R technology development. Using a randomized sample and possibly omitting them from the survey would have left serious gaps in the results of the study. Furthermore, a larger, random sample would tend to move the results toward some "average" set of responses. The aim of the interviews was to survey those at the leading edge of advanced A&R technology development and obtain an informed, critical response as opposed to an average or typical response. Although more interviews might have been desirable, the time and resources to accomplish them were not available.

2. Interview Process

The selected personnel were asked to provide their inputs to the rankings during one-hour interviews although the interviews ranged from 50 to 90 minutes. These sessions were highly structured to obtain the interviewee's utility functions and trade-off scaling constants for the set of eight attributes.

The interviews were divided into six steps (Figure 4-4). The first step involves an introduction to the study and its purpose with a presentation of the attributes and their scales and ranges. The second step elicits the utility functions for each attribute. The third step checks for independence conditions that are important for methodological reasons by asking if the responses to the questions of step 2 would vary with changes in the levels of the other attributes (attributes other than the attribute for which the utility function is being assessed). If the interviewee does believe the attributes are dependent, an additional set of questions are used to determine the conditional utility functions. The fourth step involves ranking the attributes in order of their importance. This step is used as a check for preference reversals in the fifth step where the trade-off scaling constants are obtained, to insure that responses are consistent. The sixth step is a summary of the interview process and provides the interviewee with an opportunity to make additional comments and revisions as needed.

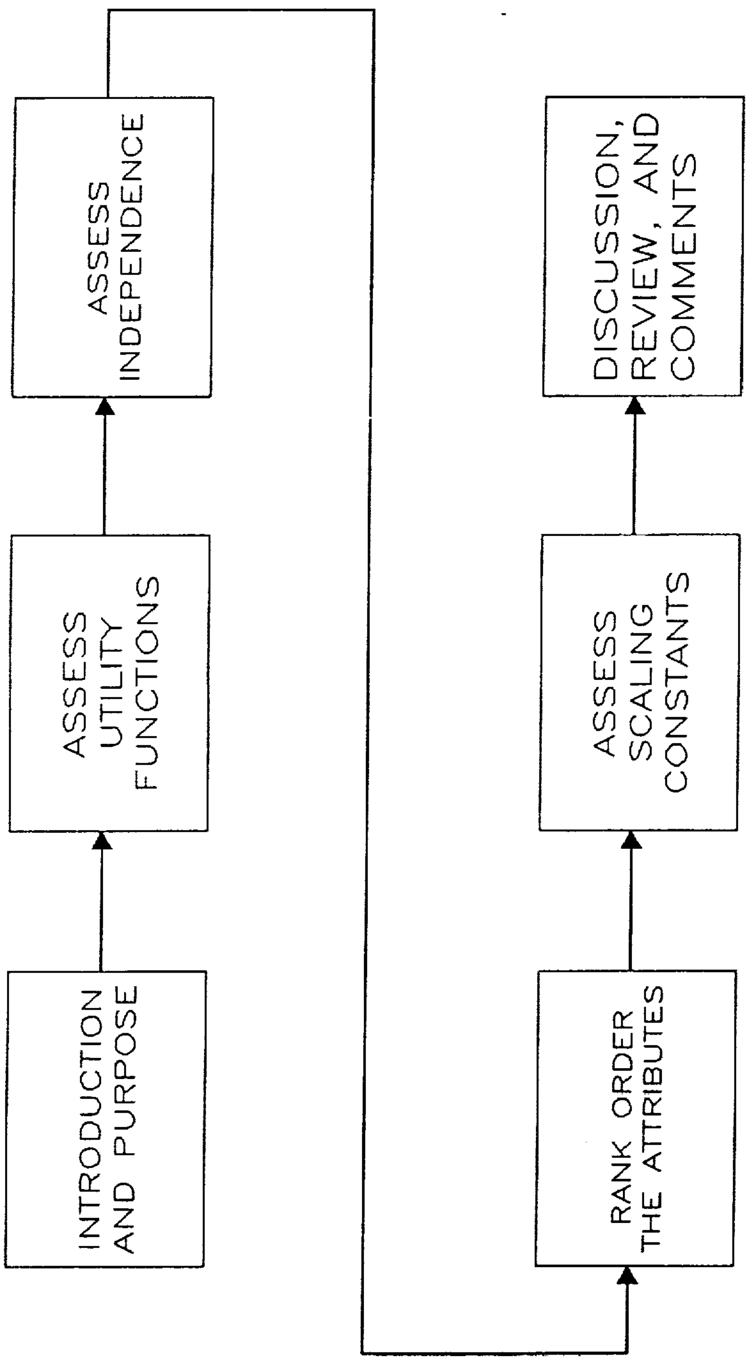


Figure 4-4. Interview Process

3. Sample Questions

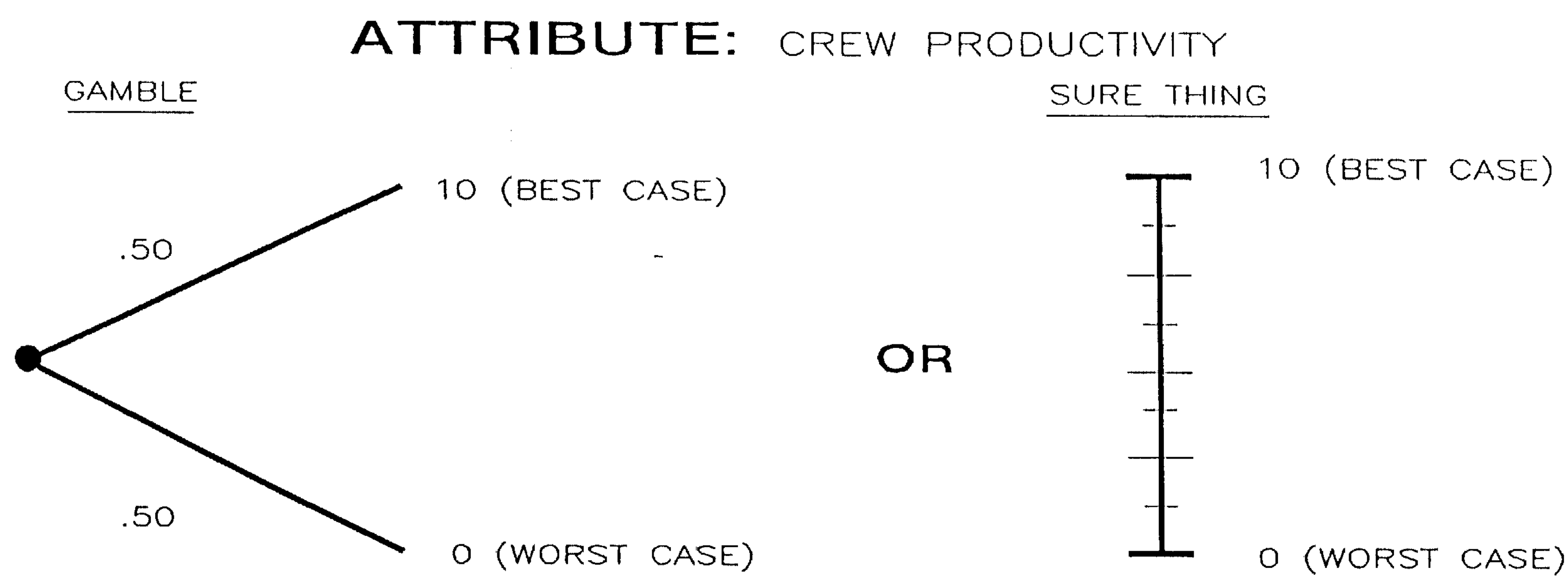
Sample questions used during the interviews are illustrated by Figures 4-5 (step 2, utility assessment), 4-6 (step 4, ranking of attributes), and 4-7 (step 5, trade-off scaling constant assessment). Figure 4-5 presents a sample question used to obtain the information needed to construct the interviewee's utility function for the attribute "growth potential." Figure 4-6 presents a sample question to obtain the interviewee's ranking of attributes by importance. Figure 4-7 shows a sample question for obtaining the scaling constant for the attribute "growth potential." The full questionnaire is contained in Appendix A of this report.

The use of interviews in the decision analysis process is well established and documented (References 42, 43, 44, and 45). The method used in the present study for utility function assessment is called the certainty-equivalent method because it involves a search for an attribute indifference point that is "certain" versus an equivalent lottery with fixed probabilities (50-50). Recent studies have focused on limitations of the certainty-equivalent process used and a number of alternative questionnaire techniques have been under development such as the lottery-equivalent method where the indifference choice is between two lotteries rather than a certainty versus a lottery (References 46 and 47). Comparison studies have not yet demonstrated improved performance of these alternate methods in an applied setting and such a comparison was beyond the scope of this study.

4. Interview Results

For the most part, the interviews went rather smoothly. All interviewees were able to provide the information needed to form their attribute utility functions and trade-off scaling constants. Table 4-11 summarizes the utility function assessment responses in two ways. The median certainty equivalents approximate the characteristics of a preferred high-leverage prototype A&R candidate. The attitudes toward risk for each of the attributes implied by the responses show that the group as a whole was risk averse to high operations cost impacts, crew productivity, and resource requirements impacts (perhaps realizing that a major benefit of A&R is generally realized during the operations phase through improved productivity and reductions in resources required). The interviewees are predominantly risk neutral for safety and development risk (perhaps assuming that minimum safety requirements will be met regardless of the high-leverage prototypes and development risk can be leveraged with additional funding). The interviewees were somewhat risk averse to initial cost attribute (high initial cost for an A&R candidate reduces cost-effectiveness) and definitely risk prone to the growth attribute (perhaps by definition, the purpose of a high-leverage prototype is implementation--not growth and there is a willingness to gamble for high values of growth as exhibited here). Another interesting case is the split in risk attitudes for spinoff potential--an equal number of risk averse, risk neutral, and risk prone responses indicating very different assumptions about the importance of spinoff potential.

Responses to the questions for ranking the importance of each of the attributes are summarized by group and for the entire sample in Table 4-12. The table presents the overall ranking of the attributes on the left and the breakdown by individual ranking in the three columns on the right. Note that these are strict ordinal rankings and the reader should not be mislead by the range of rankings. For example, in some cases the interviewee ranked two attributes equally resulting in less than eight numbers. The relevance of attribute importance is to indicate those factors which tend to influence the final rankings. The term "influence" is used because although two attributes, A and B, might be rated 1 and 4, the actual weights used in the calculations might be 0.90 and 0.88, respectively (i.e., non-linear). The conclusion to be drawn is that A is preferred to B--not that A is four times as important as B.



- FOR WHICH VALUE OF THE "SURE THING" ARE YOU INDIFFERENT BETWEEN THE "SURE THING" AND THE "GAMBLE"?

  INDIFFERENCE POINT ______

- IF YOU KNEW THAT ALL OTHER ATTRIBUTES WERE AT THEIR WORST STATES?

  INDIFFERENCE POINT ______

- IF YOU KNEW THAT ALL OTHER ATTRIBUTES WERE AT THEIR BEST STATES?

  INDIFFERENCE POINT ______

Figure 4-5. Sample Utility Function Questions

ORDER OF IMPORTANCE OF ATTRIBUTES

WHICH ATTRIBUTE WOULD YOU CHANGE FROM ITS WORST STATE TO ITS BEST STATE?

ATTRIBUTE	INITIAL COST	OPNS COST	CREW PROD.	SAFETY	DEVELOP. RISK	RESOURCE REQTS.	GROWTH POTENTIAL	SPINOFF POTENTIAL
BEST STATE	10	10	10	10	10	10	10	10
WORST STATE	0	0	0	0	0	0	0	0

ORDER OF IMPORTANCE								

Figure 4-6. Sample Ranking of Attribute Importance Question

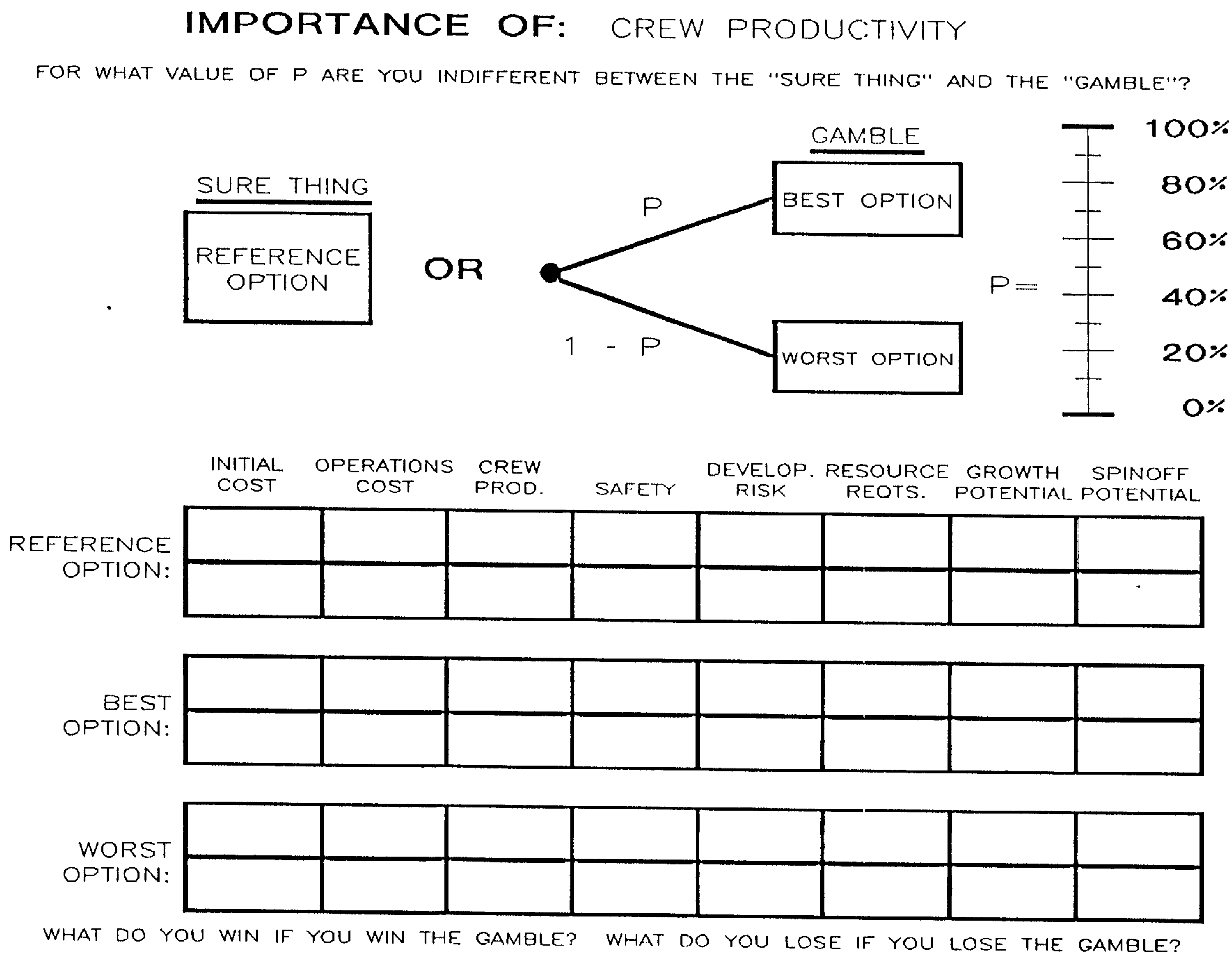


Figure 4-7. Sample Trade-off Constant Question

Table 4-11. Interview Data for Utility Responses

Attribute	Response Range	Median Response	Risk Averse	Risk Neutral	Risk Prone
Initial Cost Impacts	4.0 - 7.0	5.0	2	3	4
Operations Cost Impacts	2.5 - 7.5	3.5	$\boxed{7}$	0	2
Crew Productivity	2.5 - 8.0	5.0	$\boxed{4}$	3	2
Safety	3.5 - 8.0	5.0	3	$\boxed{4}$	2
Development Risk	4.0 - 8.0	5.0	2	$\boxed{5}$	2
Resource Requirements	2.5 - 6.5	4.5	$\boxed{5}$	3	1
Growth Potential	5.0 - 7.0	6.0	0	3	$\boxed{6}$
Spinoff Potential	2.0 - 9.5	5.0	3	3	3

Table 4-12. Interview Data for Importance of Attributes

	RANK SUM RULE RANKINGS	INDIVIDUAL RANKINGS BY GROUP		
Attribute	Rank Sum Rule Over All Groups	Level I Group	Level II Group	Third Party
Crew Productivity	1	$\boxed{1,2,4}$	$\boxed{1,1,2}$	2,3,4
Operations Cost Impacts	2	$\boxed{1,2,2}$	$\boxed{1,3,4}$	2,2,6
Initial Cost Impacts	3	2,5,6	4,5,5	$\boxed{1,1,1}$
Safety	4	1,4,6	2,2,4	3,4,7
Growth Potential	5	3,3,7	3,4,7	3,5,7
Development Risk	6	3,4,5	4,6,6	3,4,8
Resource Requirements	7	4,6,7	3,4,7	3,5,5
Spinoff Potential	8	5,8,8	4,8,8	6,6,8

The NASA group rankings (Levels I and II) reveal disparities over the priority of crew productivity versus operations cost impacts perhaps due to their common importance for operations benefits. The Third Party group disagrees completely preferring initial cost (perhaps due to the realization that many funding decisions are based on initial costs rather than operations or combined life-cycle costs). The groups tend to agree that spinoff potential is not a major factor that influences the selection of high-leverage prototyping A&R candidates. The rank sum rule described in Section III is used to collapse the individual rankings into the list on the left. Again, this ranking is ad hoc in nature and used here to simply show the general importance exhibited by the individual ranks.

An additional display of attribute importance for the most preferred and least preferred attributes is shown in Table 4-13. The apparent importance of crew productivity, operations cost, and initial cost is highlighted as is the apparent low importance of spinoff potential.

Table 4-13. Ranking of Attributes for Most and Least Important Attributes

	Number of Times Rated :	
Attribute	Most Important	Least Important
Crew Productivity	4	0
Operations Cost Impacts	6	0
Initial Cost Impacts	5	0
Safety	2	1
Growth Potential	1	3
Development Risk	1	2
Resource Requirements	0	1
Spinoff Potential	1	8

G. POST-PROCESS EVALUATION

The final step in the evaluation was to ascertain from all the participants a perception as to the strengths and weaknesses of the overall study. The post-process questionnaire is shown in Appendix D. The purpose of the post-process evaluation was to obtain an overall reaction of the participants to various elements of the study, identify areas that need improvement, and use the critique provided to determine whether the process is workable as now constituted or needs modification.

The cover letter and questionnaire were distributed to twenty individuals and a follow-up letter was sent approximately four weeks later. A total of six responses was returned (30%). The results of the post-process questionnaire are discussed in Section VI.

SECTION V

MULTIATTRIBUTE DECISION ANALYSIS MODEL RESULTS

A. OVERVIEW

This section describes the analysis performed using the data sets described in Section IV. The alternative high-leverage prototyping A&R candidates are characterized by the values of their attribute states (either point estimates or cumulative probabilities) obtained from the technical assessment committee. The preferences of the interested parties are characterized by their utility functions and trade-off scaling constants obtained during the interviews. The two datasets are combined using the multiattribute decision analysis methodology described in Section III to compute a ranking of the alternative high-leverage prototype A&R candidates. A sensitivity analysis is performed to better understand the interplay of the numerous parameters and their effects on the results. The focus of this section is a description of ranking results for the nominal case which forms the baseline result for the study. The nominal case is used as the primary basis for selecting promising high-leverage prototype A&R candidates (subject to further analysis). However, a sensitivity analysis of variations on decision model assumptions, and an analysis of the implications for the set of high-leverage prototype A&R candidates are described via a series of analysis cases.

1. Analysis Cases

Four important decision model assumptions are varied in order to test the sensitivity of the model and bound the results. The following discussion describes each of the decision model assumptions varied, the cause(s) of variation in the results (differences in ranking results), and the default decision model assumption used for the nominal case. The four decision model assumptions varied are (1) probabilistic versus deterministic analysis; (2) nominal versus best and worst case utility functions; (3) multiplicative versus additive decision models; and (4) individual preferences by interested party groups.

The first decision model assumption examined is a comparison of the rankings for the deterministic and probabilistic cases. The purpose is to identify differences between rankings in both cases to determine the impacts of including uncertainty, and to trace the sources of uncertainty. Any differences in ranking results are due to the use of attribute state cumulative distributions rather than single-valued estimates. The nominal case uses the probabilistic results.

The second decision model assumption examined is a comparison of the results implied by the nominal data and the best and worst case values obtained in the preference assessment interviews. The best and worst case values provide upper and lower boundaries for the range of ranking results as a function of dependencies between preferred attributes. Any differences between ranking results would be due to the interested party's belief that dependencies exist between attribute states. The nominal case uses the values under assumed independence.

The third decision model assumption examined is a comparison of the ranking results using two different decision models. As described in Section III and used for the nominal case, if the trade-off scaling constants do not sum to 1.0, the multiplicative model (Equations 1 and 3) is used to calculate the outcome multiattribute expected utility. However, the additive model results (which assume attribute preferential independence) can also be computed by normalizing the trade-off scaling constants to sum to one. Any differences between ranking results under this decision model assumption would be due to exclusion of the non-linear cross-terms in the multiplicative model.

The fourth decision model assumption examined is a comparison of the ranking results between groups and across groups. Differences are examined between the set of individual rankings and the rankings of subsets of individuals. There are four groups in this study: Level I, Level II, Third Party Technologists, and a combined group of all the interested parties. The nominal case is the combined group of nine interested parties.

A number of additional cases could have been constructed but were not considered within the scope and schedule of the study.

2. Computer Runs

The sensitivity analysis of the above decision model assumptions implies the calculation of forty-eight different cases:

Case	Number of Combinations	Number of Input Files
Probabilistic versus deterministic	2	1
Nominal versus best versus worst case	3	3
Multiplicative versus additive decision model	2	1
Groups 1,2,3,4	* 4	+ 4
TOTAL NUMBER	48	9

Appendix C lists the combinations of cases and output for the nominal case. A series of five-hundred and one-hundred Monte Carlo trial runs were performed in the probabilistic cases, and after determining convergence within one-hundred Monte Carlo trials, subsequent probabilistic computer runs were made at the one-hundred trial level. The output from the series of runs was printed and analyzed. The results of the analysis are presented in the following sections.

B. RESULTS FOR THE NOMINAL CASE ATTRIBUTE DATA

The computed rankings for the nominal case provide a list of rank-ordered, high-leverage prototype A&R candidates for each interested party. The analysis procedure consists of displays showing the range of rankings across the various groups summarized with a measure of group tendency (the median). The analysis discusses general observations and then focuses on the top ten high-leverage prototype A&R candidates and the results of varying a number of decision model assumptions. A comparison of the results is made to separate evaluations conducted by A&R working groups and an overall summary of results is presented.

The overall rankings across interested parties are summarized in Figure 5-1 and the separate group I, II, and III rankings are presented in Figures 5-2, 5-3, and 5-4 (see Table 4-1 for the definitions of the high-leverage prototypes). Each high-leverage prototype A&R candidate is listed on the x-axis and the integer rank order (1,2,3, ...) is plotted on the y-axis (note that a ranking of 21st is _most_ preferred). The figure is derived in two steps. The first step involves subtracting one standard

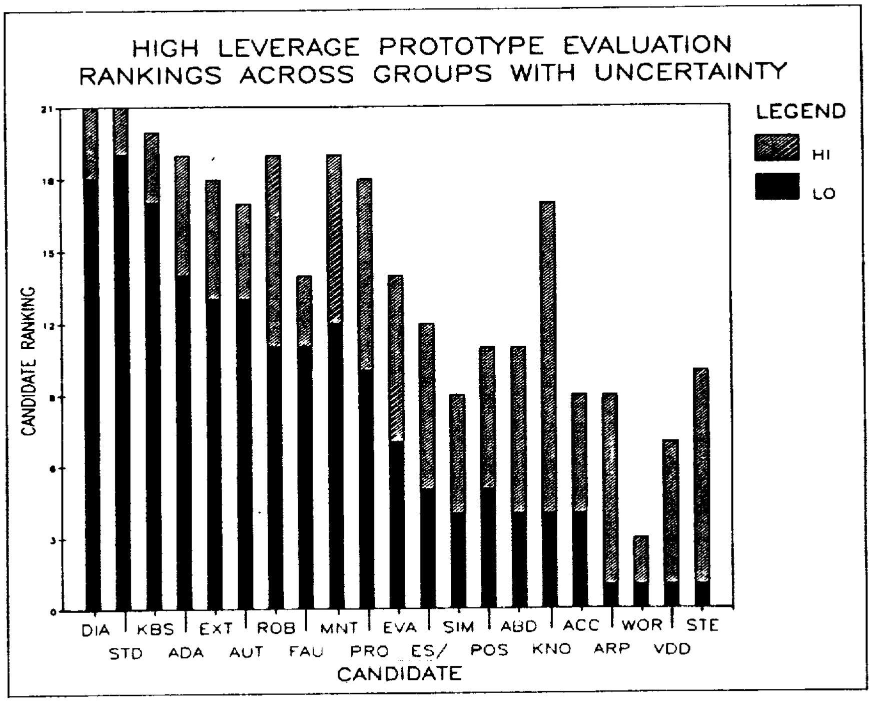


Figure 5-1. Probabilistic Rankings, All Groups Combined

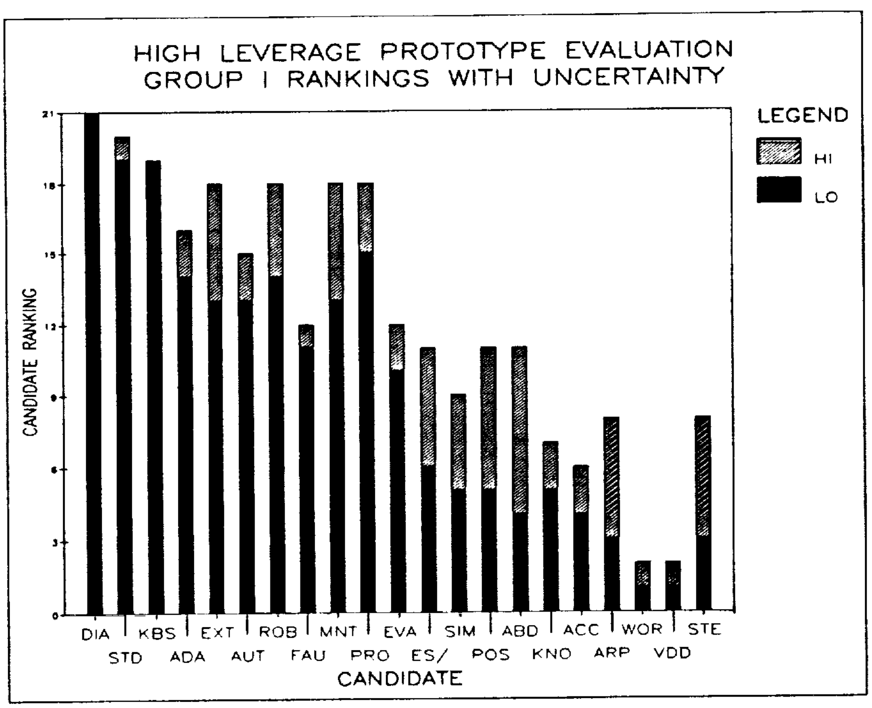


Figure 5-2. Probabilistic Rankings, Level I Group

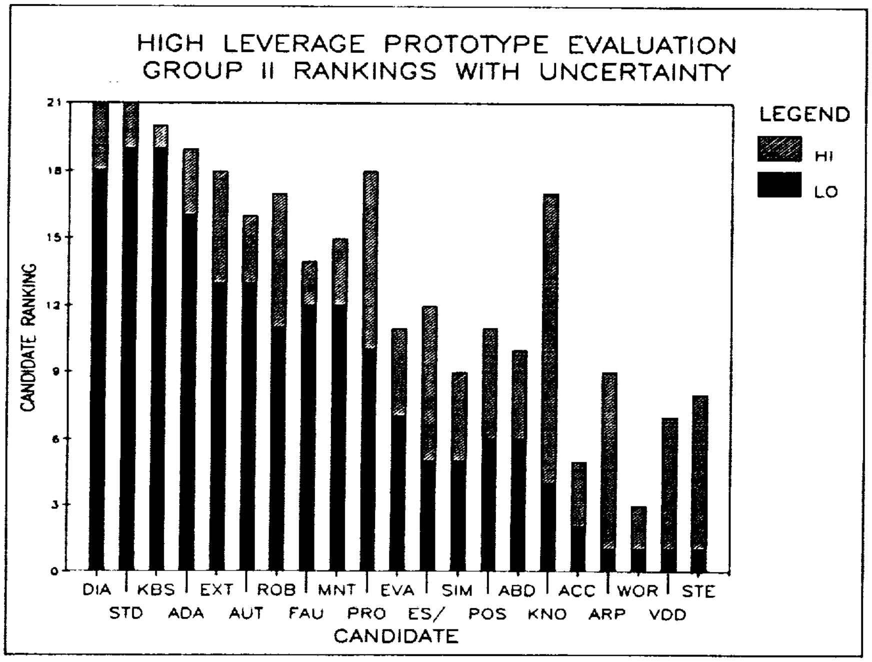


Figure 5-3. Probabilistic Rankings, Level II Group

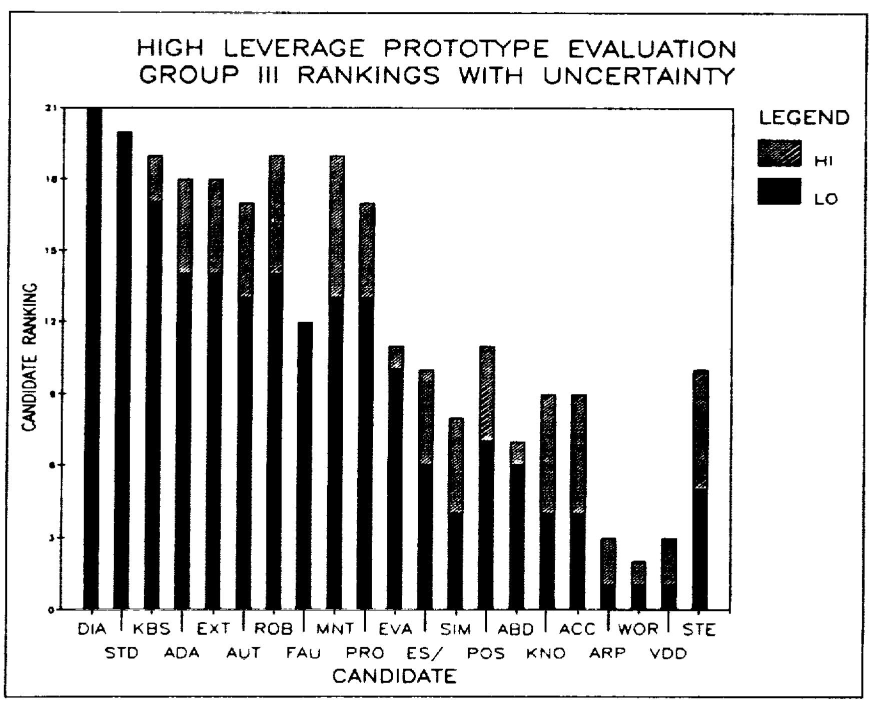


Figure 5-4. Probabilistic Rankings, Third Party Group

deviation from each outcome utility mean and rank ordering the high-leverage prototype A&R candidates. The second step involves adding one standard deviation to each outcome utility mean and rank ordering the high-leverage prototytpe A&R candidates. The range of results is then plotted on Figure 5-1 as a range of low and high across all nine interested parties. Thus, the range displays the overall position of each high-leverage prototype A&R candidate relative and the variation due to a combination of attribute state uncertainties and interested party preferences.

Figure 5-1 highlights an immediate problem of how to interpret the results. A simplistic approach entails ranking the alternatives based on the median of the nine rankings for each high-leverage prototype A&R candidate. However, the variation associated with each candidate provides a measure of the associated uncertainty. The question ultimately becomes, "Should the high-leverage prototype A&R candidates be rank ordered based on value only (e.g., the median) or on value plus uncertainty?" This question points to a common trade-off facing technical management--whether to select a high value, highly uncertain option, or select a lower value, low uncertainty option. Rather than select one approach, both are presented here.

Figure 5-1 does show, in a general sense, the high-leverage prototype A&R candidates in descending order of preference. The DIA, STD, and KBS options are most preferred while ARP, WOR, and VDD are least preferred. Although the range of variation appears to diminish with value, a number of high-leverage prototype A&R candidates with very wide ranges are interspersed in the list, namely ROB, MNT, PRO, and KNO. Some of this uncertainty can be traced to the Level II group for the cases of PRO and KNO. The broad range is due to a difference of opinion in the Level II group. This can also be seen by comparing Level I (Figure 5-2) and the third party group (Figure 5-4) to the Level II group (Figure 5-3). Note that Level I and the third party group have much smaller ranges and in some cases no range (indicating the members agreed on that high-leverage prototype A&R candidate rank), while the Level II group has a much wider range. In fact, one individual representing an operations perspective in the Level II group widens the range not only for that group but for the combined group (Figure 5-1) as well. This is due, in part, to interviewee number two's higher importance for safety and a lower importance for crew productivity than other members of the group:

Attribute	Level II Interviewee Trade-off Weights/Importance Rank 1	2	3	Candidate Attribute States[1] PRO	KNO
Crew Productivity	0.65/2	0.30/3	0.50/1	7.5	5.0
Safety	0.55/4	0.50/1	0.40/2	3.3	5.5
Growth Potential	0.60/3	0.05/4	0.25/4	7.0	6.0
Spinoff Potential	0.25/8	0.05/4	0.25/4	7.5	1.5
Initial Cost	0.50/5	0.50/1	0.25/4	5.0	8.0

The attribute states for PRO indicate a low safety contribution, but high marks for growth and spinoff potential--attributes of least importance to the interviewee number two. The result is a much lower ranked PRO than the other interviewees. The KNO case is misleading because although the weights between individual number one and two are the same, initial cost is ranked fifth and first, respectively. Thus, the high attribute state for initial cost receives substantially more weight by individual number two, resulting in a higher ranked KNO than that of interviewees one and three.

[1] CDF's represented by mean value.

The above description typifies the discussion used to explain why an alternative occupies a particular position in the rankings. The focus of attention is now directed at a subset of the high-leverage prototype A&R candidates near the top of the list. Because no information was available on actual budget or number of high-leverage prototype A&R candidates to be selected, the top ten options were chosen for closer examination.

The problem raised by Figure 5-1 is addressed in Figure 5-5. The rankings are displayed by group in two ways. A "flow" diagram is used to present the group rankings under two decision rules each represented by a column on the left and right. Beginning at the top, the options are ordered from most preferred to least preferred. The first decision rule selects preferred high-leverage prototype A&R candidates based on their value only (the median of the outcome expected utility rankings for the individuals in the group). Using this rule, the user follows the left-hand path down the list. The second decision rule selects preferred options based on their value first, and in the event of ties, on minimum variance. Using the second rule, the user follows the right-hand path down the list. Note that in some places, one column indicates an identical ranking under both decision rules.

Figure 5-5 shows similar concordance between the Level I and the third party group--the Level II group reverses the order of DIA and STD for reasons as discussed earlier. An indicator of the robustness of the model is the commonality of the top ten lists (the same set of ten high-leverage prototype A&R candidates appears in all four lists). Furthermore, the top three high-leverage prototype A&R candidates are the same in all four lists, DIA, STD, and KBS.

It is interesting to note that the top three high-leverage prototype A&R candidates are software-related to the fields of artificial intelligence and expert systems. Two of the applications are error/fault detection systems and the third is a study of standards and tools to facilitate expert system development.

C. RESULTS OF VARIATIONS ON THE NOMINAL CASE

A series of runs with the multiattribute nominal, best-, and worst-case data were made to examine variations in the nominal results to (1) deterministic rankings; (2) the preferences of the interviewees (best and worst cases); and (3) the additive decision model form. The nominal case described above is used as the basic model (using the probabilistic case with nominal interviewee preference data and multiplicative decision model). The first comparison involves the nominal case versus all the deterministic cases. The second comparison involves the nominal case versus all the best and worst case options. The third comparison involves the nominal case versus all the additive decision model cases. Table 5-1 displays the variety of combinations for analysis.

All comparisons are made using the rank sum rule outcomes to reduce computational complexity and highlight any large effects. The rank sum rule is applied across all nine individuals in the three groups to summarize major effects (the discussion of group differences is presented in section D). The basis for computing the rank sum rankings is integer ranking value.

1. Probabilistic Versus Deterministic Results

Table 5-2 displays the nominal rankings with differences in numerical rank from the six deterministic cases. Thus a blank space indicates no difference between the nominal case and the corresponding comparison case. A positive number indicates the specific high-leverage prototype A&R

HIGH-LEVERAGE PROTOTYPE EVALUATION
UNCERTAINTY CASE TOP TEN

RANK	GROUP I		GROUP II		GROUP III		ALL	
1	DIA		STD		DIA		STD	
2	STD	KBS	DIA	KBS	STD		DIA	
3	KBS	STD	KBS	DIA	KBS		KBS	
4	PRO	PRO	ADA	ADA	ROB	ADA	ADA	
5	ROB	ADA	EXT	AUT	ADA)	EXT	EXT	AUT
6	EXT)	ROB	AUT	EXT	EXT	ROB	AUT	EXT
7	MNT	AUT	ROB	ROB	MNT	AUT)	MNT	MNT
8	ADA	EXT)	PRO	PRO	PRO	PRO	ROB	FAU
9	AUT	MNT	MNT	FAU	AUT	MNT	PRO	ROB
10	FAU	FAU	FAU	MNT	FAU	FAU	FAU	PRO

OBSERVATIONS: HIGHER VARIATION IN GROUP II REPLICATED.
GROUPS I AND III SIMILAR IN CONCORDANCE.
TOP 3 ARE: STD, DIA, KBS.
TOP 10 ARE SAME PROPOSALS IN SLIGHTLY DIFFERENT ORDER.
) DENOTES A TIE.

NOTE: DECISION RULE
VALUE ONLY ↙ ↘ VALUE+ RISK

Figure 5-5. Probabilistic Results, Top Ten

Table 5-1. Sensitivity Analysis Combinations (Common Dimensions in Boxes)

Interviewee Responses (Nominal, Best, Worst)	Uncertainty Model (Deterministic or Probabilistic)	Decision Model (Multiplicative/Additive)
Nominal Case Ranking		
Nominal	Probabilistic	Multiplicative
Deterministic Cases		
Nominal	Deterministic	Multiplicative
Best	Deterministic	Multiplicative
Worst	Deterministic	Multiplicative
Nominal	Deterministic	Additive
Best	Deterministic	Additive
Worst	Deterministic	Additive
Nominal vs. Best and Worst Cases		
Best	Probabilistic	Multiplicative
Best	Probabilistic	Additive
Best	Deterministic	Multiplicative
Best	Deterministic	Additive
Worst	Probabilistic	Multiplicative
Worst	Probabilistic	Additive
Worst	Deterministic	Multiplicative
Worst	Deterministic	Additive
Nominal vs. Additive Decision Model		
Nominal	Probabilistic	Additive
Best	Probabilistic	Additive
Worst	Probabilistic	Additive
Nominal	Deterministic	Additive
Best	Deterministic	Additive
Worst	Deterministic	Additive

Table 5-2. Comparison of Nominal to Deterministic Results[2]

		Difference in Ranking from Nominal Case					
Candidates	Nominal Case	DET NOM MULT	DET BEST MULT	DET WORST MULT	DET NOM ADD	DET BEST ADD	DET WORST ADD
DIA	1						
STD	2						−1
KBS	3						+1
ADA	4		−1	−2			
EXT	7				+1		
AUT	9				+1		
ROB	4			−1	−1	−1	−2
FAU	10						
MNT	8			+1	−1		
PRO	6			+2	−1	+1	+1
EVA	11						
ES/	13	−1		+1	+1		+1
SIM	16		+1			+1	
POS	12			−2	−1		−2
ABD	15				+1	+1	+2
KNO	14	+1		+2	−1	−2	
ACC	18			−1			
ARP	19			+2			
WOR	21						
VDD	20						
STE	17			−1			
Concordance Among Individuals:	0.93	0.93	0.93	0.94	0.94	0.95	0.95
Agreement:	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Concordance Between Rankings:	1.00	0.999	0.999	0.998	0.997	0.998	0.994
Agreement:	Yes	Yes	Yes	Yes	Yes	Yes	Yes

[2]DET denotes deterministic case; NOM, BEST, and WORST denotes nominal, best, and worst case interviewee data; MULT denotes multiplicative model; and ADD denotes additive model. Blanks represent agreement with Nominal Case ranking.

candidate moved up in the rankings by that value, and a negative number indicates the candidate moved down in the rankings from the corresponding nominal value. The number indicates how far the high-leverage prototype A&R candidate moved up or down. Examining Table 5-2 reveals how little the deterministic decision model assumption affects these results--at most, two positions for 9 of the 126 possible positions and one position for 26 of the 126 positions (91 positions remained unchanged by the decision model assumption variations).

The majority of ranking changes (10) occurs in the deterministic worst case/multiplicative model. The second model with the largest number of changes (7) is the deterministic worst case/additive model, suggesting that the worst case interviewee responses may be the root causes of the differences. These results indicate a number of the interviewees believed that their preference for the state of an attribute was affected more if the other attributes were at a worst state than at their best state.

The concordance shown at the bottom of the table measures the degree of agreement between rankings. The upper concordance among individuals is the degree of agreement across all nine individual rankings. A "Yes" indicates the null hypothesis of independence of rankings could not be rejected at a 95% level of significance. Note that all such tests performed in the study use a 95% significance level. The lower concordance value is the degree of agreement between the nominal case and each decision model. As shown, there is strong agreement for the rankings as a whole, although the DET/WORST/ADD case is the lowest. (Also note that the concordance between rankings for the Nominal Case will always be 1.0 by definition.)

2. Nominal Versus Best and Worst Cases

Table 5-3 displays the results of the comparisons between the nominal case and the best case interviewee responses. Again, there is, at most, an exchange of two positions (2 out of 84 possible occurrences), an exchange of one position in some cases (16 out of 84 possible occurrences), and no change in the majority of cases (66 out of 84 possible occurrences). Overall, the ranking positions of 18 out of the 84 possible positions are affected.

Table 5-4 displays the results for the comparison between the nominal case and the worst case interviewee responses. The differences between best and worst case responses identified in the deterministic case earlier are evident here. While the number of changes in ranking position is at most two (for 12 out of 84 possible occurrences) and in some cases one (for 24 out of 84 possible occurrences), there is clearly more shifting due to the worst case data (36 out of 84 possible positions). This can also be seen in all concordance values when compared to the best case (see Table 5-3).

3. Comparison of Decision Models

Table 5-5 displays the results for the comparison between the nominal case and the additive decision model. There is, at most, an exchange of two positions (7 out of 126 possible occurrences), an exchange of one position in some cases (37 out of 126 possible occurrences), and no change in the majority of cases (82 out of 126 possible occurrences). Overall, the ranking positions of 44 out of the 126 possible positions are affected.

Table 5-3. Comparison of Nominal to Best Case Results[3]

		Difference in Ranking from Nominal Case			
Candidates	Nominal Case	BEST PROB MULT	BEST PROB ADD	BEST DET MULT	BEST DET ADD
DIA	1				
STD	2				
KBS	3				
ADA	4	−1		−1	
EXT	7		+1		
AUT	9				+1
ROB	4		−1		−1
FAU	10				
MNT	8				
PRO	6				+1
EVA	11				
ES/	13				
SIM	16		+1	+1	+1
POS	12				
ABD	15	+1	+1	−1	+1
KNO	14	−1	−2		−2
ACC	18				
ARP	19				
WOR	21				
VDD	20		−1		
STE	17				
Concordance Among Individuals:	0.93	0.95	0.96	0.94	0.95
Agreement:	Yes	Yes	Yes	Yes	Yes
Concordance Between Rankings:	1.00	0.999	0.998	0.999	0.998
Agreement:	Yes	Yes	Yes	Yes	Yes

[3]DET denotes deterministic case; NOM, BEST, and WORST denotes nominal, best, and worst case interviewee data; MULT denotes multiplicative model; and ADD denotes "additive" model. Blanks represent agreement with Nominal Case ranking.

Table 5-4. Comparison of Nominal to Worst Case Results[4]

		Difference in Ranking from Nominal Case			
Candidates	Nominal Case	WORST PROB MULT	WORST PROB ADD	WORST DET MULT	WORST DET ADD
DIA	1				
STD	2		−1		−1
KBS	3		+1		+1
ADA	4	−2		−2	
EXT	7	−1			
AUT	9				
ROB	4	−1	−2	−1	−2
FAU	10				
MNT	8	+1		+1	
PRO	6	+2	+1	+2	+1
EVA	11				
ES/	13	+1	+1	+1	+1
SIM	16		+1		
POS	12	−1	−1	−2	−2
ABD	15		+1		+2
KNO	14		−2	+2	
ACC	18	−1		−1	
ARP	19	+1		+2	
WOR	21				
VDD	20		−1		
STE	17			−1	
Concordance Among Individuals:	0.93	0.94	0.95	0.94	0.95
Agreement:	Yes	Yes	Yes	Yes	Yes
Concordance Between Rankings:	1.00	0.996	0.996	0.996	0.991
Agreement:	Yes	Yes	Yes	Yes	Yes

[4]DET denotes deterministic case; NOM, BEST, and WORST denotes nominal, best, and worst case interviewee data; MULT denotes multiplicative model; and ADD denotes "additive" model. Blanks represent agreement with Nominal Case ranking.

Table 5-5. Comparison of Nominal to Additive Decision Model Results[5]

		Difference in Ranking from Nominal Case					
Candidates	Nominal Case	NOM PROB ADD	BEST PROB ADD	WORST PROB ADD	NOM DET ADD	BEST DET ADD	WORST DET ADD
DIA	1						
STD	2			−1			−1
KBS	3			+1			+1
ADA	4						
EXT	7	+1	+1		+1		
AUT	9				+1		
ROB	4	−1	−1	−2	−1	−1	−2
FAU	10						
MNT	8				−1		
PRO	6	−1		+1	−1	+1	+1
EVA	11						
ES/	13	+1		+1	+1		+1
SIM	16		+1	+1		+1	
POS	12	−1		−1	−1		−2
ABD	15	+1	+1	+1	+1	+1	+2
KNO	14	−1	−2	−2	−1	−2	
ACC	18						
ARP	19						
WOR	21						
VDD	20	+1	+1				
STE	17						
Concordance Among Individuals:	0.93	0.95	0.96	0.95	0.94	0.95	0.95
Agreement:	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Concordance Between Rankings:	1.00	0.998	0.987	0.996	0.997	0.998	0.991
Agreement:	Yes	Yes	Yes	Yes	Yes	Yes	Yes

[5] DET denotes deterministic case; NOM, BEST, and WORST denotes nominal, best, and worst case interviewee data; MULT denotes multiplicative model; and ADD denotes additive model. Blanks represent agreement with Nominal Case ranking.

4. Work Package Overlaps

Because of the proposal submission process, areas of overlap exist, not only across the high-leverage prototype A&R candidates, but also between some of the candidates and the S.S. *Freedom* Program Work Packages (References 48 through 51). Before a high-leverage prototype A&R candidate can be recommended for funding, it is reviewed for both types of overlap. When areas of overlap are identified, reductions in scope may or may not be required. Overlap in some areas may, in fact, be necessary to reduce risk or to provide management with alternative approaches. In such cases, reductions in scope would not be required. Other overlap areas may be eliminated to avoid duplication or control cost. Reductions in scope are recommended in such cases. Such decisions must be made on a case-by-case basis. One of the purposes of the "DECISIONS TO FUND" box is to make such determinations in light of technical risks and budget constraints.

Three courses of action are possible. Surviving proposals can: (1) be incorporated into rescoped Work Packages; (2) be incorporated into existing (unmodified) Work Packages; or (3) be funded under separate contract. This process is illustrated in Figure 5-6. All proposals were reviewed and Table 5-6 illustrates both types of overlap and recommendations.

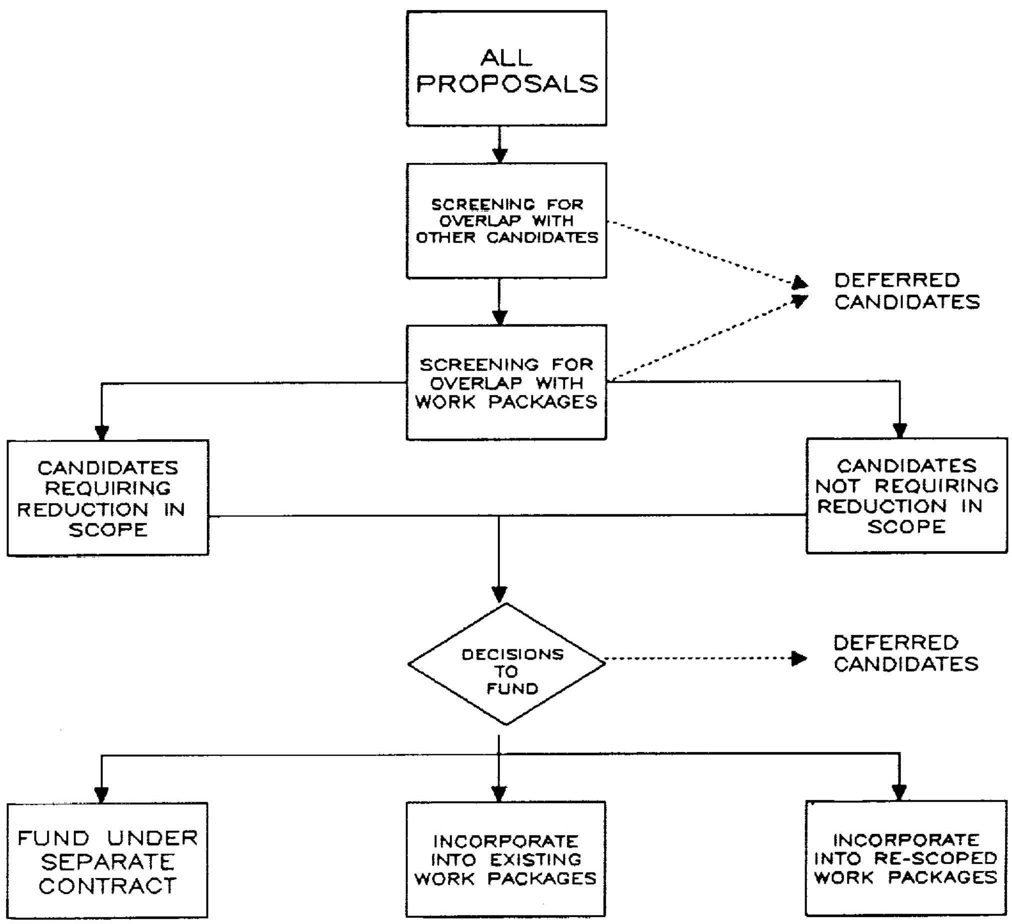


Figure 5-6. Process for Resolution of High-Leverage Prototype Overlaps

Table 5-6. Areas of Work Package/High-Leverage Prototype Overlap

IDENTIFIER	TITLE	NOTES
DIA	Diagnostic EPS	Proposal for a hierarchical diagnostic ES[6] for EPS integrated with DMS. Some overlap with WP4 (see Reference 48 pp. A-13 to A-26). Should be integrated with WP4.[7]
STD	Stds/Tools for ES	No apparent overlap.
KBS	Fault redundancy management	WP2 proposed ES for FDIR in DMS/OMS plans[8] (see Ref. 49 pp. 1-99 to 1-104).
ADA	ADA Effectiveness	WPs 2 (see Ref. 49, p. 1-99), 4 accept ADA as the given language and are proceeding with software development. Therefore the issue of ADA effectiveness is moot.
EXT	Extended fault-tolerant testbed	No apparent overlap.
AUT	Auto Robotic Assy	Some overlap with ROB. Both propose a facility that emulates shuttle-based control of robot(s) for assembly; should be integrated with each other and ultimately with WP 3 (see Reference 51).
ROB	Robotic control SS Assembly	Some overlap with AUT. Both propose a facility that emulates shuttle-based control of robot(s) for assembly; should be integrated with each other and ultimately with WP 3 (see Reference 51).
FAU	Fault Prediction for Electrical Equipment	Identifies fault prediction of electrical equipment as goal of KBS. WP 4 identifies ES in baseline configuration (see Ref. 48, pp. A-1 to A-25). Candidate would transfer on-line predictive system to S.S. *Freedom* Program. Should be integrated with DIA and then WP 4.
MNT	KBS[9] Development and Maintenance	Some overlap with KNO, ES/. Any proposal to define KBS standards must necessarily include knowledge acquisition (KA) standards. KBS development maintenance may also overlap the ES standards research.

[6]ES: Expert System.

[7]EPS: Electric Power Subsystem; DMS: Data Management Subsystem; WP 4: Work Package 04 (Reference 48).

[8]FDIR: Fault Detection, Isolation, and Recovery; OMS: Operations Management Subsystem; WP 2: Work Package 02 (Reference 49).

[9]Knowledge-Based System.

Table 5-6. Areas of Work Package/High-Leverage Prototype Overlap (Continued)

IDENTIFIER	TITLE	NOTES
PRO	Prototype Scheduler	Some overlap with WP 2 (see Reference 49, pp. 1-102 to 1-103).
EVA	EVA Retriever	Dropped from WP contracts; NASA in-house effort.
ES/	ES Stds Research	Some overlap with MNT, KNO. Any proposal to define KBS standards must necessarily include KA standards. KBS development maintenance may also overlap the ES standards research.
SIM	Auto Robotic Simulation	No apparent overlap.
POS	Telerobotic and Thermal Posture Predictor	WP 2 includes thermal prediction model (see Reference 49, p. 1-32). Use of FTS[10] is unclear.
ABD	Abductive Tech.	No apparent overlap.
KNO	Knowledge Acquisition Standards	Some overlap with ES/, MNT. Any proposal to define KBS standards must necessarily include KA standards. KBS development maintenance may also overlap the ES standards research.
ACC	Accel SSM Demo	Acceleration of existing effort; no apparent overlap.
ARP	A&R Prototyping	WP 1 lists as part of A&R: risk-level BIT/BITE on-board maintenance system (see Reference 50, p. 1-59).[11]
WOR	World Modeling	No apparent overlap.
VDD	VDDT to OMA	No apparent overlap.
STE	Stereo Telepresence	No apparent overlap.

[10] Flight Telerobotic Servicer.

[11] WP01: Work Package 1 (Reference 50); BIT/BITE: Built-in Test/Built-in Test Equipment.

The following brief summary is helpful in relating Work Package responsibilities to high-leverage prototype A&R candidate overlap areas.

A number of potential overlap areas have been identified. In most cases the information in the proposals is inadequate to provide full resolution. Before a final assessment of overlap can be completed, fact-finding sessions are required. Proposers would be required to resubmit additional information in the indicated areas. Table 5-7 summarizes the situation at the present time.

Table 5-7. Work Package Overlaps

Candidates ↓ Degree of Overlap Identified →

Definite	Possible/ Potential	None Apparent	Unknown	Moot
DIA				
			STD	
	KBS			
				ADA
		EXT		
AUT				
ROB				
FAU				
MNT				
PRO				
				EVA
ES/				
		SIM		
POS				
		ABD		
KNO				
		ACC		
	ARP			
		WOR		
		VDD		
		STE		

There are a number of potential overlaps among the submissions. There are also large inconsistencies in quality and completeness among the alternative high-leverage prototype A&R candidates, particularly in coordination with the Work Packages. These potential overlaps are identified and recommendations made for resolution. In some cases, a high-leverage prototype A&R candidate is recommended for incorporation into a Work Package. For these cases, the choice between direct incorporation and increased contract scope is a decision for the cognizant Work Package Center.

5. Comparison to Working Group Evaluations

During the course of the study, the AAWG, RWG, and AIESTWG conducted independent evaluations of the high-leverage prototype A&R candidates within their respective areas. The working group evaluations used a variety of criteria and weighting procedures different from the methodology of this study. Thus, it is easier to assess where differences exist rather than why they exist. However, some general observations can be made. Figure 5-7 summarizes the working group results and the study results. The candidates enclosed in boxes represent matches with the top ten high-leverage prototype A&R candidates obtained by the study methodology. While there are agreements between the top ten list and the working group list, there are also discrepencies. It is impossible to ascertain what the working group rankings might have been for a merged list, however, it is reassuring that numerous matches do exist.

D. CONCORDANCE OF RANKINGS

This section presents and discusses the results of the concordance calculations for the rankings presented earlier (see Section III-C for a discussion of concordance statistics). Three different types of concordance were calculated and analyzed:

(1) Individual rankings within groups.
(2) Group rankings with different decision rules.
(3) Group rankings using different multiattribute decision model assumptions.

The purpose of the concordance analysis is to assess the sensitivity of the rankings to differences among individuals within groups; differences in group decision rules; and variations in decision model assumptions regarding the decision models used. The results are summarized in Table 5-8. Overall, the rankings are highly concordant for all three cases implying that the rankings presented earlier are robust under a variety of conditions.

The concordance of the rankings given to the twenty-one alternative high-leverage prototype A&R candidates by individuals in the four groups studied was examined in two ways: (1) by comparing the individual rankings within groups for each of the 48 computer runs described earlier in this section; and (2) by comparing the group rankings according to the additive, Nash, and rank sum rules (see Table 5-8). The following observations can be made:

(1) There is not perfect agreement throughout the rankings.

(2) There are several instances where the ranks assigned to several alternatives by one interviewee in a group appear to be at variance from those given by the other interviewees in the group, particularly for the Level II group. Because the lowest concordances in the table are between the deterministic and probabilistic nominal cases, this may be attributable to differences in attitude toward risk.

(3) The concordance measures are in every instance, highly significant. Each case is statistically significant below the 5% level.

(4) A detailed comparison of rankings was performed to examine the effects of varying the decision model assumptions (see Section C). While the model was still robust and agreement obtained, the WORST case option has the lowest concordance within the variety of decision model assumptions studied. As in (2) above, this may be due to the interviewees' risk aversion to an indifference point when all the remaining attributes are at their worst state. However, the fact remains that although the risk aversion may have been an effect, it is not significant at the 95% level.

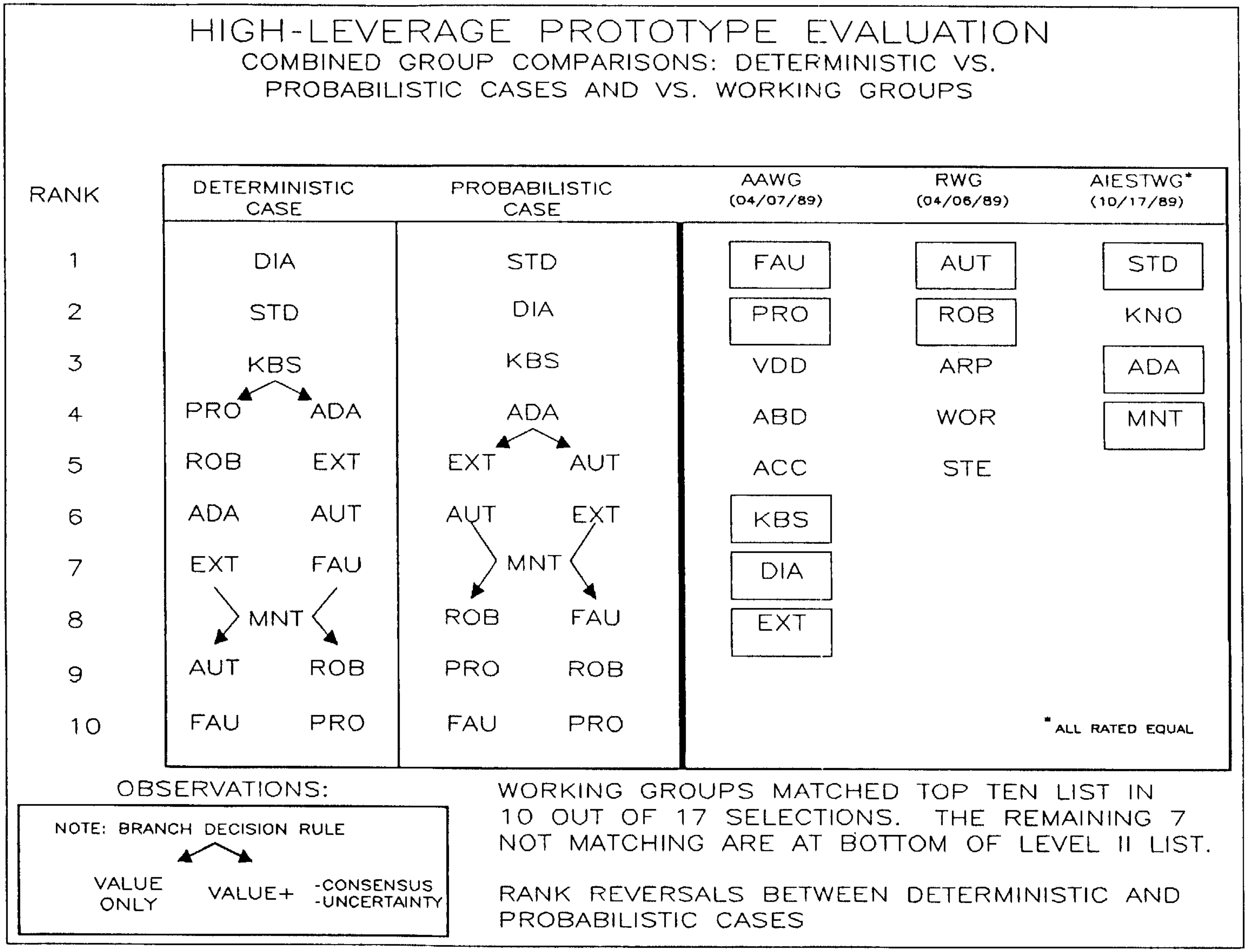


Figure 5-7. Comparison to Working Group Rankings

Table 5-8. Concordance Analysis Results

HIGH-LEVERAGE PROTOTYPE EVALUATION
CONCORDANCE ANALYSIS

D/P: DET/PROB
N/B/W: NOM/BEST/WORST CASE
M/A: MULT/ADD DECISION MODEL
OVER 4 GROUPS = 2•3•2•4=48 CASES

	GROUP I		GROUP II		GROUP III		ALL	
	I	G	I	G	I	G	I	G
D/N/M	0.97/A	1.00/A	0.90/A	1.00/A	0.96/A	1.00/A	0.93/A	1.00/A
P/N/M	0.98/A	1.00/A	0.90/A	0.99/A	0.97/A	1.00/A	0.93/A	1.00/A
P/N/A	0.98/A	1.00/A	0.92/A	1.00/A	0.97/A	1.00/A	0.95/A	1.00/A
D/N/A	0.92/A	1.00/A	0.97/A	1.00/A	0.96/A	1.00/A	0.94/A	1.00/A
D/B/M	0.92/A	0.99/A	0.98/A	1.00/A	0.97/A	1.00/A	0.94/A	1.00/A
D/W/M	0.95/A	0.99/A	0.95/A	1.00/A	0.97/A	0.99/A	0.94/A	1.00/A
P/B/M	0.93/A	0.99/A	0.98/A	1.00/A	0.97/A	1.00/A	0.95/A	1.00/A
P/W/M	0.95/A	0.99/A	0.96/A	1.00/A	0.97/A	1.00/A	0.94/A	1.00/A
D/B/A	0.94/A	1.00/A	0.90/A	1.00/A	0.97/A	1.00/A	0.95/A	1.00/A
D/W/A	0.95/A	1.00/A	0.90/A	1.00/A	0.97/A	1.00/A	0.95/A	1.00/A
P/B/A	0.95/A	1.00/A	0.92/A	1.00/A	0.98/A	1.00/A	0.96/A	1.00/A
P/W/A	0.96/A	1.00/A	0.97/A	1.00/A	0.98/A	1.00/A	0.95/A	1.00/A

(5) As a result, by each of the comparison methods, there is substantial agreement in the rankings of the twenty-one high-leverage prototype A&R candidates within each of the four groups analyzed and for the variations in decision model assumptions performed.

It should be noted that the high levels of concordance should not be inferred to mean there are no disagreements in rankings. As shown earlier in Tables 5-2 through 5-5, small numbers of position changes do occur. The task remains for the Associate Director to weigh the effects of these small changes together with the degree of work package overlap and any other programmatic considerations before selecting a recommended set of high-leverage prototype A&R candidates.

SECTION VI

DISCUSSION AND CONCLUSIONS

A. DISCUSSION

To place the results of the study in context with the Space Station Program, two issues should be considered:

(1) What are the goals (values to be maximized) that should be used to evaluate the high-leverage prototype A&R candidates?

(2) What steps need to be taken to implement the study results within the S.S. *Freedom* baseline?

The purpose of high-leverage prototype A&R candidates is to provide near-term, low-risk capabilities for inclusion in the baseline S.S. *Freedom.* With respect to the first issue, if the value to be maximized is high-value with high-risk, then a different perspective and rank ordering is implied (see Figure 6-1). A legitimate role for NASA could be the subsidization of risky technology developments with high payoffs. Such an approach could yield larger potential benefits for commercial spinoffs than the alternatives implied by this study. If the low-risk definition of a high-leverage prototype is maintained, the approach followed here is appropriate. However, if the restriction that the technologies be baselined is relaxed and the evolution-phase is considered, long-term "risky" technology developments could be subsidized and candidates with larger variances could then be included.

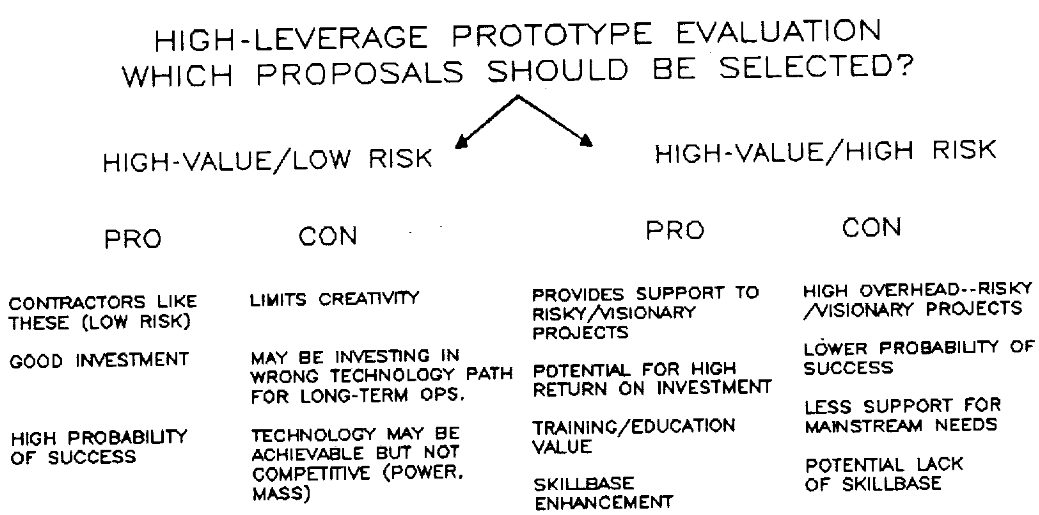


Figure 6-1. Alternative High-Leverage Prototyping Program Goals

The second issue is one of logistics. After a final set of high-leverage prototype A&R candidates is established, candidates with work package overlaps may need rescoping. In addition, if any high-leverage prototype A&R candidates are being funded from other sources, at the decision point to select a high-leverage prototype, the funding for that source should be coordinated between the appropriate S.S. *Freedom* offices to formalize management control and responsibility of the technology development.

As a process, the approach of this study required a number of adaptive "adjustments." The aim of the process was to facilitate the programmatic evaluation of A&R candidates to relieve some of the overload at the working group level and ensure consistent, objective evaluation. However, due to internal working group difficulties, the attribute state data required for this study were developed by a third party technical committee. There were additional complications in task progress due to frequent management turnover within the S.S. *Freedom* Program (3 Associate Administrators and 5 Directors during the course of the study).

Irrespective of the turbulence in the external environment, the process did move forward. Was the process a good one? Was the process effective in meeting the objectives outlined in Section I? To address some of these issues, a post-process assessment questionnaire was mailed to the participants after the results had been presented (see Appendix D). While approximately one-third of the twenty participants responded (30%), it should be noted that the number of returned questionnaires may be insufficient to draw definitive conclusions. Table 6-1 summarizes the responses received. Overall, the results indicate a majority of responses with a good-to-excellent rating, however, there were a number of problem areas needing improvement.

On the positive side, there was general agreement that the process of ranking was useful both for improving understanding and evaluation. Four participants responded that the process would be useful in future evaluations, while two felt it would not. Intuitive concurrence with the results was rated good with one exception. Of the four who answered the question, antigaming safeguards were judged fair-to-excellent.

On the negative side, it was mentioned that the proposers of the high-leverage prototype A&R candidates were not represented well by their submitted proposals alone. This belief almost certainly resulted from the informal nature of the call for high-leverage prototype A&R candidates and delays in their evaluation. If the study had been intended solely as an exercise, then the usual protocols restricting contact between evaluator and proposer would most likely have been eased or eliminated.

The reasonableness of the ground rules was judged as good, and the handling of uncertainties was also above average. The overall credibility of the technical assessment process, however, was judged as only average--perhaps due to concerns about the informality of the original call. Finally, the group decision rules were judged to be good.

There was no general agreement on the preferred process for future evaluations, but the results (five out of six) indicate a desire to have some type of computerized decision support capability for the participants. Comments about the use of argumentation analysis regarded the process as useful. However, the analytic, labor-intensive nature of describing each argument component was a tedious process that could be facilitated by the use of a software database tool to enter, edit, and manage the large quantities of text information. A number of comments reflected a sense that the argumentation analysis provided a balance between the quantification of the vast array of numerical attribute state inputs and thinking behind each high-leverage prototype A&R candidate.

Table 6-1. Post-Process Questionnaire Results

A. YOUR OVERALL REACTION TO THE EVALUATION	Unsatisfactory	Poor	Fair	Good	Excellent	NA[1]
(1) Describe the value of ranking the A&R candidates in improving your understanding of them.	☐	☐	2	3	1	☐
(2) Describe the value of rankings for evaluating A&R candidates.	☐	☐	1	2	3	☐
(3) Describe the usefulness of the results for measuring candidate value.	☐	1	2	3	☐	☐
(4) Describe the effectiveness of the safeguards in preventing "gaming" by the participants.	☐	☐	2	1	1	2
(5) Describe the fairness of the process from the proposers' point of view.	☐	2	2	2	☐	☐
(6) Describe the fairness of the process from your point of view.	☐	1	1	4	☐	☐
(7) Describe the efficiency of the process for generating final rankings	☐	1	1	2	2	☐
(8) After examining the results, describe your intuitive concurrence.	1	☐	1	3	1	☐
(9) Describe the utility to you of similar processes in future evaluations.	1	1	☐	2	2	☐
B. THE TECHNICAL ASSESSMENT PROCESS						
(1) Describe the reasonableness of the ground rules.	☐	1	1	2	2	☐
(2) Describe the adequacy of the process in addressing the uncertainties in candidate attributes.	☐	☐	3	1	2	☐
(3) Describe the validity of using arguments for and against the attribute ratings in establishing technical credibility.	☐	☐	2	3	☐	1
(4) Describe the credibility of the technical assessment process.	☐	2	2	2	☐	☐
(5) Describe the adequacy of the technical assessment process in preventing "gaming."	☐	☐	3	1	1	1
C. THE ASSESSMENT OF PRIORITIES						
(1) Describe the adequacy of SSF Decision Maker representation, given the scope of the evaluation.	☐	1	1	2	1	1
(2) Describe the utility of the group decision rules for expressing group preferences.	☐	☐	1	3	☐	2
TOTAL RESPONSES:	2	10	25	36	16	7
PERCENTAGE:	2%	10%	26%	38%	17%	7%

(3) If asked to participate in a future evaluation, would you prefer a process with:

Analyst support only?	Interactive computer support with analyst backup?	Stand-alone computer software with analyst coordination?
1 response	3 responses	2 responses

[1]NA: Not applicable or no response.

Objections to the methodology were not specific to the multiattribute decision analysis model or framework other than the comment mentioned in Section IV, but were aimed at the potential of participants to bias the results. These concerns are common to any type of evaluation using virtually any model. However, the original objectives were to develop:

(1) A consistent basis for evaluation.
(2) A mechanism for reaffirming or checking the analysis of the A&R candidate advocates.
(3) An aggregation of input from all concerned parties, based on a consistent set of program evaluation attributes.
(4) A trial application of a proven tool for the A&R implementation and evaluation process.

It is apparent that a consistent basis for evaluation was developed and applied to a set of A&R candidates. The approach is consistent in the sense that the same decision model was applied to each high-leverage prototype A&R candidate in the same computational manner.

A mechanism was established to confirm the analysis of high-leverage prototype A&R candidate advocates. There were some disagreements between the working group evaluations and the study results, but the results match for the majority of high-leverage prototype A&R candidates.

A collection and aggregation of input was obtained from concerned parties based on a common set of program evaluation attributes. Whether all the concerned parties were represented is a matter for debate. Additional time might have allowed a separate interested party group for the operations perspective, however the scope and timing of the analysis and resources involved did not indicate a need for a large number of interest groups during the course of the study. There were a number of comments made prior to the application of the process:

Comment (1):
"The evaluation process should allow those who assign ratings for the attributes to choose a range of values within which the actual value is felt most likely to reside. The proposals and the criteria are both difficult to quantify and the sensitivities of the evaluation results to variations in attribute scores should be made visible in the final output (Reference 52)."

Comment (1) refers to the issue of transparency--that the process allow the users to provide estimates in an understandable format that conveys the meaning and the message. If a numerical value cannot be estimated, it should be acceptable to indicate such a response and continue with the process. Furthermore, the sensitivities of the results to variations in attribute ratings and interviewee responses should be displayed in an intuitive manner. The sensitivity analysis approach examines variations in the decision model and input data sets using statistical concordance of rankings. As shown in Section V, there is sensitivity to changes in model assumptions but not statistically significant sensitivity. This does not imply that such changes (at most two ranking positions) could not be important. Depending on how resources are allocated, such differences could be significant to high-leverage prototype A&R candidates at the margin--those candidates that might not be selected due to a change in ranking of two positions. While budgeting strategies and R&D portfolio considerations are beyond the scope of this study, it is possible to devise strategies for dealing with such issues (e.g., building redundancy into the program to reduce risk by splitting and redistributing resources across the marginal projects).

Comment (2):
"The true value of your analysis methodology is in the iteration with the proposal evaluators to force them to think about the real value of the proposal as opposed to the "technical beauty" of the proposal. I am sure we all agree that the output of a computer algorithm should not be used to select the proposals for funding without further "sanity" checks (see Reference 52)."

Comment (2) is a reminder that people, not computers and algorithms, make the important decisions. This fact was recognized at the outset of the study and reaffirms the need for the decision maker to synthesize not only the information contained in this study and degree of work package overlaps, but also the programmatic risks and uncertainties and other factors impinging on the selection of an appropriate set of high-leverage prototype A&R candidates.

Comment (3):
"... The major difficulty is that there will be either insufficient knowledge or proposal content to enable the reviewers to accurately position each proposal in the set of attributes that you have provided. I think the exercise will enable us to see just how much subjectivity is present in an evaluation of this type. Also, I think it is valuable to see the variation in answer ranges for each of the people rating the proposal to get some idea of the degree of consensus (or lack thereof). Means/averages are not sufficient. Through several iterations with the same group of reviewers, I think we can refine things to the point that we might become comfortable with the process (Reference 53)."

Comment (3) again raises the issue of high levels of uncertainty inherent in the set of high-leverage prototype A&R candidates studied and how variations in their attribute states impact the resulting rankings. As described in this publication, the methodology presented provides a way of incorporating multiple attributes with different levels of uncertainty to allow the use of actual cumulative probability distribution functions and thus characterize the impacts of a broad array of uncertainties on the final ranking outcome. These variations are shown to have minimal impact on the final ranking values and consensus for the case study presented herein. However, for other applications, these impacts would be quantifiable and traceable for cases where consensus did not exist.

The main theme of contention with the approach is a "concern" that the inputs of each participant are reviewed and available to the other participants as a method of checks and balances to ensure that biases are minimized and fairness prevails. Whether this reflects a commonplace desire to simply understand the process in a transparent manner is unclear. However, the issue is relevant for future studies and evaluations and is discussed in Section 6-C.

B. PROGRAMMATIC IMPLICATIONS OF THE RESULTS

The analysis has four implications based on interviews with NASA personnel, the analysis methods, and the results obtained.

The first implication is that high-leverage prototyping is beneficial to the Space Station *Freedom* Program as a means for transferring technology from the advanced development program to the baseline program. The gap between the research and implementation phases of a technology has traditionally presented both a barrier and an opportunity to the utilization of that technology. The barrier results from the lack of a clear and credible message from the technologist to the potential user that the technology already has clear applications, rather than being a solution in search of a problem. While most technologists would claim this for their own technology, there is such a barrage of these messages that the user must have some reliable means to sift through them. The opportunity is that a program manager can allocate resources to a high-leverage prototyping program, selected according to the method outlined in this report, that will reveal and foster those technologies that have higher maturities and probabilities of success.

The second implication is the study provides guidance as to which areas for the set of twenty-one high-leverage prototype A&R candidates are promising. They include:

DIA	Diagnostic Expert System for electric power and data management
STD	Standards and Tools for Expert Systems
KBS	Knowledge-based system for fault detection in data management and operations management systems
EXT	Testbed for extended fault-tolerant testing
AUT	Study of robotics for assembly and fasteners with testbed
FAU	Knowledge-based system for electric power subsystem fault prediction
MNT	Study of knowledge-based system development and maintenance tools
ROB	Software upgrades to demonstration of robotic control of assembly
PRO	Prototype crew scheduler using advanced search methods

Thus, even if a high-leverage prototyping program does not become an on-going process, the above technologies could make a positive contribution to the baseline S.S. *Freedom*. There will always be some hesitation to accept automatically, the results of such evaluations. Uncertainties necessarily play a major role in any selection. Reviewers must pay particular attention to this issue. Examining the above list, two commonalities are apparent.

The first commonality is that virtually all of these recommended high-leverage prototyping A&R candidates involve software (DIA, STD, KBS, FAU, MNT, ROB, and PRO) as opposed to hardware elements (EXT, AUT). The software emphasis focuses primarily on the application of Expert System and Knowledge-Based Systems to S.S. *Freedom* subsystems with high potential for early benefits: the electric power, data management, and operations management subsystems. This may be due, in part, to earlier studies indicating the application potential of these technologies and subsystems (Reference 54) cited by a number of the high-leverage prototyping A&R candidates. A secondary, but important, emphasis in the list involves the study of support tools for the development of Expert and Knowledge-Based Systems (STD, MNT).

The second commonality is that virtually all of the high-leverage prototyping A&R candidates involving applications to hardware focus on the same subsystem areas. This was also true to some extent, for the full list of candidates. The most common concept was the study of some aspect of fault detection, fault tolerance, and fault prediction related to the electric power subsystem. There was also interest in applications for the data management and operations management subsystems.

The resulting focus of the high-leverage prototyping A&R candidates on automation applications may be a facet of the trade-off between implementation needs and schedule risk. As stated earlier, the purpose of the high-leverage prototyping activity is to leverage advancing A&R technologies into the baseline S.S. *Freedom*. An implication of this study is that software (automation) candidates represent a class of technologies well suited for late addition to the baseline S.S. *Freedom* design. As a high-leverage A&R candidate increasingly involves the development or testing of hardware, the time requirements for development can increase and pressure the decision (by increasing the schedule risk) to include or not include the candidate in the baseline. Such risks can be mitigated if the hooks and scars for the technology are in the baseline, because the technology can be added at any time. However, if the hooks and scars are not present, a high-leverage prototype that is not ready on time will need to be redesigned or (possibly) dropped from consideration. Such reasoning might explain why most of the recommended candidates involve software developments. It is more likely that two world views exist. The first world view believes that software development is inherently risky and that the purpose of the high-leverage prototyping program is to encourage risky prospects. The second world view believes that software development is low in risk and thus improves the likelihood that the high-leverage prototyping A&R candidate will be implemented in the baseline S.S. *Freedom* design. Whether the different types of high-leverage prototyping A&R candidates were presorted by the proposers based on these different world views is unknown, because the original definition of the high-leverage prototyping program included both notions of investing in ***high-risk candidates*** with the objective of ***implementation*** in the baseline design.

The third implication of the study is the risks and uncertainties associated with advanced technologies can be quantified in a manner that surfaces the relevant issues for decision making in those highly uncertain environments. The analysis of the decision model inputs has shown that the intuitively high level of uncertainty associated with the twenty-one high-leverage prototype A&R candidates is reflected numerically in the variance of both the attribute states and the resulting expected utility value used to rank order the alternatives. The question still remains whether high uncertainty, as exhibited by high variance, is a positive or negative feature of the high-leverage prototype A&R candidate. Any high-leverage prototyping program needs to understand and determine whether to subsidize high-value low-risk developments or high-value high-risk developments. Because the programmatic interest for this study is to make the high-leverage prototype A&R candidate a feature of the near-term baseline, pragmatic considerations favor the low uncertainty, low-risk candidates. However, in an environment where hooks and scars exist for high-leverage prototype A&R candidates, high-risk developments would not incur the severe cost and schedule penalties of a "no-go" decision and could be implemented later in the evolutionary phase. A fundamental question for technical managers of such R&D programs is how to balance risks. For example, during the early stages of project development, the R&D portfolio might consist of primarily high-risk tasks with a small number of low-risk tasks. As the project draws closer to finalization of the design, the mixture of tasks would shift toward fewer high-risk tasks with a majority of low-risk tasks.

The fourth implication is the potential to automate and transfer various elements of the process using software tools to provide, for example, a distributed decision support system for use by the participants; a tool for group decision conferencing and post-process analysis; a tool for assisting the technical assessors in providing the probabilistic data for the attribute states; or a tool to facilitate the construction of supporting arguments for the argument analysis. Such tools can eliminate much of the bookkeeping associated with the databases and computations and allow the participants more freedom to focus on the decisions to be made. It is also important to note that the multiattribute decision analysis process used in this study is not constrained in any fashion to the evaluation of high-leverage prototypes. The same approach has been applied in many different types of technology evaluations and could be used in other S.S. *Freedom*, Lunar exploration, and Mars exploration technology-related decision-making contexts as such programs evolve.

C. LIMITATIONS AND AREAS FOR FUTURE IMPROVEMENTS

1. Limitations

Two factors that limited the study were the inconsistencies in quality and completeness of data for the various high-leverage prototype A&R candidates. There was no common format to be followed, inadequate data were submitted in many cases, and a number of high-leverage prototype A&R candidates were not coordinated with the work packages. Because of limited resources, it was not possible to formally validate the data provided, hence, all attributes used in the evaluation were subjective and thus subject to uncertainty. Although these uncertainties are large for specific attribute states, they were not judged to have significant impact on the consensus of the resulting rankings. In fact, these uncertainties highlight the differences between a low and high-risk high-leverage prototyping program and the need to determine an appropriate role for NASA for funding such an R&D program.

C-2

During the technical assessment, a secondary set of attributes was assigned to different assessors for the purpose of cross-checking the attribute state ratings between different individuals. However, there were insufficient resources to recalculate a second analysis and examine the impacts of using these alternative inputs on the results. It would be useful to complete the secondary analysis as an alternative benchmark from which to judge the consistency of the technical assessments.

A third factor was the scope of the interested party interviews. Although the number of interviewees (11) may have been appropriate for the size of the evaluation, it would have been useful to interview representatives from upper S.S. *Freedom* Program management areas and additional representatives from the operations areas.

2. Future Improvements

Four improvements to the process were identified for future applications.

The first improvement would require the establishment of common goals and perspectives prior to the call for concepts. An element of setting such goals would be the development of an attribute list to facilitate the collection of more complete attribute information according to a common format. The requirements for completion of these attributes would be provided to the proposer when the call for proposals is made.

The second area for improvement would be the establishment of an on-going A&R function at the systems engineering and integration level with a single focal point of responsibility to coordinate such evaluations for the variety of anticipated A&R candidates, including the high-leverage prototype A&R candidates. Should specific high-leverage prototype A&R candidates be funded and pursued, additional data could be used to perform more detailed analyses of the selected candidates for validation purposes.

The third area for improvement would be the development of a group process for review and selection of the high-leverage prototyping A&R candidates. For the current study, this step was performed by the authors. However, the questionnaire respondents indicated a desire to monitor the data and decision algorithms during the process rather than at the end of the process when it is difficult to modify elements of the process. The review process could take the form of a "decision" conference involving the decision making participants, the analysts, and video display of the decision variables and data.

A fourth area for improvement to the process would be the addition of a user-friendly decision support system (DSS) helpful to development, evaluation, comparison, and application of the high-leverage prototyping A&R candidates. The DSS could help answer a wide variety of "what-if?" questions and should provide transparency (or visibility) into the causes of the results. The argumentation analysis of the attribute state ratings would also be much easier if a simple data entry and database management tool were available to help the technical assessors step through each question. Such a DSS could support a group of decision makers in a conferencing environment with a single projected video display. An alternative would be a DSS used by the analysts to prepare a distribution file for individual participants using a microcomputer-based program and the case-specific data diskette.

D. CONCLUSIONS AND RECOMMENDATIONS

A number of conclusions and recommendations can be drawn from this study:

1. The Process

(1) The first implication is that high-leverage prototyping is beneficial to the Space Station *Freedom* Program as a means for transferring technology from the advanced development program to the baseline program. Such a mechanism serves as a formal bridge between technology development programs and end-users. The bridge, however, needs to be specified with greater detail.

(2) The purpose of high-leverage prototype A&R candidates is to provide near-term, low-risk A&R applications for inclusion in the baseline S.S. *Freedom*. The interest in low-risk development for this application is to make the application part of the near-term baseline. High risk developments could also be considered if evolutionary applications are included. Any high-leverage prototyping R&D program should determine whether to subsidize high-value, low-risk developments or high-value, high-risk developments. The needs in both cases are different.

(3) The application of multiattribute decision analysis methods was useful for meeting the numerous requirements and constraints specific to the S.S. *Freedom* Program. In particular, the ability of the methodology to address multiple attributes with uncertainty, multiple interested parties to the decision, and monitoring of consensus was seen to be effective and practical.

(4) The process would be facilitated by computer-based interactive programs to enter and edit the evaluation problem to the extent that major steps could be automated. Such a Decision Support System (DSS) for use in a distributed fashion by individuals or as a central display for decision conferencing by a group would allow greater flexibility for examining alternative assumptions. Similar software could also be developed for conducting the argumentation analysis of the technical assessment.

2. The Application

(1) Promising technology areas of potential relevance to the S.S. *Freedom* are:

DIA*	Diagnostic Expert System for electric power and data management
STD	Standards and Tools for Expert Systems
KBS*	Knowledge-based system for fault detection in data management and operations management systems
EXT	Testbed for extended fault-tolerant testing
AUT*	Study of robotics for assembly and fasteners with testbed
FAU*	Knowledge-based system for electric power subsystem fault prediction
MNT*	Study of knowledge-based system development and maintenance tools
ROB*	Software upgrades to demonstration of robotic control of assembly
PRO*	Prototype crew scheduler using advanced search methods

*Possible overlap with existing work packages and/or with other high-leverage prototyping A&R candidates.

(2) The results of this study are supported by the separate working group evaluations although a number of serious differences were observed. These differences may be attributable to the use of primarily technical criteria as opposed to the Level II S.S. *Freedom* Program criteria outlined in this study.

(3) The majority of recommended high-leverage prototyping A&R candidates involve the study or development of software either for specific applications to systems or to support the software development process in some manner. The high values for software-oriented applications may be a reflection of two world views: (i) high-leverage prototyping should encourage high-risk investments and software developments are perceived as risky; or (ii) high-leverage prototyping should encourage low-risk investments to increase the potential for inclusion in the baseline S.S. *Freedom* and software developments are perceived as low-risk. It is not clear whether or how these world views might have affected the types of high-leverage prototype A&R candidates at the point of submittal.

(4) The applications of the recommended high-leverage prototyping A&R candidates focus primarily on fault detection, fault tolerance, and fault prediction software using Expert Systems and Knowledge-Based Systems. The target subsystems for these applications are the electric power subsystem, the data management subsystem, and the operations management subsystem.

3. The Model Results

(1) The high-leverage prototype A&R candidates examined exhibit high degrees of uncertainty based in part, on schedules and deliverables. Lack of detailed proposal data is likely to have had some, albeit non-quantifiable, effect.

(2) The use of probability distributions is helpful for aggregating and quantifying the magnitude of uncertainties.

(3) The use of argument analysis, although time-consuming, proved useful for expressing the underlying patterns of reasoning for the numerical estimates of the attribute states. The numerical estimates provided a measure of the uncertainty whereas the argument analysis provided a window for the credibility of the estimates. The process used would be aided considerably by a computer-based interactive system.

(4) There is a high degree of concordance (agreement) in the rankings at both the individual and group levels. There is similar robustness under different decision model assumptions. This is due to the comparable weightings assigned to the evaluation attributes by the interested parties interviewed.

4. Recommendations

(1) A high-leverage prototyping program should require the establishment of common goals and perspectives prior to the call for concepts. An element of setting such goals would be the development of program criteria to facilitate the collection of more complete information using a common format.

(2) If a high-leverage prototyping program is initiated, a formal call for proposals should be accompanied by a prescribed set of programmatic A&R evaluation attributes and a common response format, to the extent feasible.

(3) Establish an on-going A&R function at the systems engineering and integration level to support programmatic evaluations and systems engineering trade studies for the S.S. *Freedom* Program. Such a function has never been formally established within the S.S. *Freedom* Program.

(4) Develop and implement a concrete plan for A&R/new technology implementation and incorporation within the S.S. *Freedom* Program and constitute the plan into an operational process.

SECTION VII

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APPENDIX A

GLOSSARY

A&R	Automation and Robotics
AAWG	Advanced Automation Working Group
AIESTWG	Artificial Intelligence and Expert Systems Technology Working Group
Attribute	Measurable quantity used to establish the performance and value of a high-leverage prototype A&R candidate
Code ST	TBD
DDT&E	Design, Development, Testing, and Evaluation Costs (Includes software costs)
DMS	Data Management System
ES	Expert System
FTS	Flight Telerobotic Servicer
High-leverage prototype A&R candidate	Type of A&R candidate with high potential for contribution to baseline S.S. *Freedom*. Leveraging refers to expectation that modest investment in the prototype will lead to early benefits in baseline S.S. *Freedom* design.
JEM-RMS	Japanese Experiment Module--Remote Manipulator System
KA	Knowledge Acquisition
KBS	Knowledge-Based System
OMS	Operations Management System
SSRMS	Space Station Remote Manipulator System
SPDM	Special-Purpose Dextrous Manipulator
RWG	Robotics Working Group
Work Package	Group of contractors constructing elements of S.S. *Freedom*. There are four work packages

APPENDIX B

INTERVIEW QUESTIONNAIRE FOR PREFERENCE ASSESSMENT

NASA LEVEL II AUTOMATION AND ROBOTICS CANDIDATE EVALUATION:

HIGH-LEVERAGE PROTOTYPES

QUESTIONNAIRE FOR OBTAINING PREFERENCE INFORMATION FOR USE IN RANKING A&R PROPOSAL CANDIDATES

INTERVIEWEE: ______________________________

AFFILIATION: ______________________________

LOCATION: ______________________________

DATE: ______________________________

INTERVIEW #: ______________________________

PURPOSE OF THE INTERVIEW

THE PURPOSE OF THE INTERVIEW IN WHICH YOU ARE BEING ASKED TO PARTICIPATE IS TO COLLECT THE JUDGMENTS OF LEVEL II DECISION MAKERS REGARDING IMPORTANT FACTORS TO CONSIDER IN RANKING A&R PROPOSALS.

THE QUESTIONS ARE AIMED AT OBTAINING YOUR PREFERENCES FOR SEVERAL FACTORS (E.G., COST, PRODUCTIVITY, ETC.) PERTINENT TO THE IDENTIFICATION OF PROMISING CONCEPTS FOR FURTHER DEVELOPMENT.

THE RESPONSE OF ALL PERSONS INTERVIEWED WILL BE INCORPORATED IN THE RANKING OF A&R CANDIDATES. THE INTERVIEW IS DESIGNED TO TAKE 60 MINUTES.

AUTOMATION AND ROBOTICS CANDIDATES: HIGH-LEVERAGE PROTOTYPES

THE A&R PROPOSAL CANDIDATES SPAN A VARIETY OF SPACE STATION FREEDOM TECHNOLOGIES, SUBSYSTEMS, DESIGN ENVIRONMENTS AND WORK AREAS ACROSS BOTH HARDWARE AND SOFTWARE

THE EVALUATION CONSISTS OF 21 CANDIDATES.

SPACE STATION FREEDOM REQUIREMENTS

- LOW INVESTMENT COST
- LOW OPERATIONS COSTS
- MAXIMIZE CREW PRODUCTIVITY
- MAXIMIZE SAFETY
- MINIMIZE DEVELOPMENT RISK
- MINIMIZE RESOURCE CONSTRAINTS
- MAXIMIZE GROWTH POTENTIAL
- MAXIMIZE SPINOFF POTENTIAL

ATTRIBUTES AND THEIR RANGES

ATTRIBUTE	RANGE WORST CASE	 BEST CASE
INITIAL (DDTE) COST SAVINGS	0	10
OPERATIONS COST	0	10
CREW PRODUCTIVITY	0	10
SAFETY	0	10
DEVELOPMENT RISK	0	10
RESOURCE REQUIREMENTS	0	10
GROWTH POTENTIAL	0	10
SPINOFF POTENTIAL	0	10

Attribute Scale for Initial Cost Impacts

Value	Scale Rating	Attribute Description
Best Case	10	Funding of this proposal will substantially reduce DDT&E and system integration costs for the Phase I SSF. Very large net initial cost savings.
	8	This proposal will reduce systems integration costs and potentially reduce DDT&E costs for the Phase I SSF. Initial cost savings from the investment are very likely.
	6	This proposal will have minimal DDT&E cost savings for the Phase I SSF. Impacts are likely during the operations/evolution phase.
	4	Proposal supports SSF assembly but DDT&E costs could be significant.
	2	Proposal supports SSF assembly but DDT&E costs could be large. Some issues for systems integration.
Worst Case	0	Proposal provides minimal SSF benefits at high cost. Significant system integration costs.

Attribute Scale for Operations Cost Impacts

Value and Scale Rating	On-Orbit Costs Description	Ground Operations Costs Description	Crew Training Costs Description
Best Case 10	Large expected O&M savings due to implementation of proposal deliverables. Savings are more than A&R alone; cross-cutting technology savings are likely. Savings extend across SSF lifetime	Large O&M savings due to proposal are robust--savings impacts will be obtained for grnd ops. across SSF lifetime.	Large O&M savings on costs due to implementation of proposal deliverables are likely.
7	O&M savings are focused within specific subsystems. Savings extend across SSF lifetime.	Significant grnd. O&M savings across SSF lifetime sufficient to break even against DDT&E cost.	Significant O&M savings on training costs.
5	O&M savings are likely and primary savings are expected during the 1st half of the SSF lifetime.	Grnd. O&M savings are sufficient to break even when weighed against initial investment cost (DDT&E). Savings will occur during 1st half of SSF lifetime.	Some O&M savings in crew training costs.
3	O&M savings are expected during the 2nd half of the SSF lifetime.	Grnd. O&M savings are uncertain and likely to occur during the 2nd half of the SSF lifetime.	The crew training benefits for the proposal are uncertain.
0 Worst Case	O&M savings are likely to be negative (no savings).	Grnd. O&M savings are likely to be negative.	Negative O&M savings on crew training costs.

Attribute Scale for Crew Productivity Impacts

Value	Scale Rating	On-Orbit Productivity Description	Ground Productivity Description
Best Case	10	Very large improvements in crew productivity are likely if the proposal deliverables are implemented.	Large improvements in ground crew productivity are likely.
	7	Significant Improvements in crew productivity are likely.	Significant improvements in ground crew productivity are likely.
	5	Some improvements in crew productivity are likely.	Some improvements in ground crew productivity are likely.
	3	Few improvements in crew productivity are likely if the proposal deliverables are implemented.	Few improvements in ground crew productivity are likely.
Worst Case	0	Little if no improvements in crew productivity are likely.	No improvements in ground crew productivity.

Attribute Scale for Safety

Value and Scale Rating	On-Orbit Safety Description	Ground Safety Description
Best Case 10	Very large improvements in crew safety are likely if the proposal deliverables are implemented. Adds safety benefits beyond those achievable with man-in-the-loop due to high speed computing and/or reduction in EVA. Hazards can be mitigated by diagnosis and transition of system to automated "safe-hold" mode.	Large improvements in ground safety are likely.
8	Moderate safety improvement is likely. Proposal technologies will increase safety via moderate reductions in required EVA.	Moderate improvements in ground safety are likely.
6	Some improvements in safety. Implementation of proposal deliverables likely to increase safety by preventing improper or ill-defined command sequences from entering the control system. No major effects on EVA activity.	Some improvements in ground safety are likely.
4	Minor improvement in safety. Addition of proposal deliverables increases safety in specific areas by monitoring critical functions and data reduction of SSF status to smaller numbers of parameters. No expected effects on EVA.	Minor improvements in ground safety are likely.
2	Little improvement in safety. Addition of proposal technology may be for reasons other than safety but benefits may be accrued to safety in specific (and perhaps unlikely circumstances). There may be a small increase in required EVA.	Little, if any improvement in ground safety is likely.
0 Worst Case	No improvements in safety above minimum requirements.	No improvements in ground safety above minimum requirements.

Attribute Scale for Development Risk

Value	Scale Rating	Attribute Description
Best Case	10	Virtually no development risk; off-the-shelf technologies; primarily modifications to the current system--mainly software; minimal hardware modifications; no testbed facilities required; low cost.
	7	Some development risk; testing required for minor interfaces and verification purposes; existing testbeds can be modified and used; software and hardware modifications required; demonstrated feasibility; low level cost uncertainties.
	5	Moderate risk development; some elements may require experiments and ground testing; some new testbed facilities are required; demonstrated feasibility; moderate cost.
	3	High-risk development; numerous elements require ground testing; new testbeds need to be constructed; some in-space testing; feasibility relatively certain.
Worst Case	0	Very high-risk development; elements at this level not demonstrated; may not be feasible. Requires new testbed concepts be constructed.

Attribute Scale for Resource Requirements Impacts

Value and Scale Rating	Power	Non-Consumables Upmass	Consumables Upmass
Best Case 10	The proposal implementation could result in large power savings.	Large savings in non-consumables is likely.	Large savings in consumables is likely.
8	The proposal could result in significant power savings.	Moderate savings in non-consumables is likely.	Moderate savings in consumables is likely.
6	The proposal could result in some power savings.	Some savings in non-consumables is likely.	Some savings in consumables is likely.
4	The proposal could yield minor savings in power.	Minor savings in non-consumables is possible.	Minor savings in consumables is possible.
2	The proposal would have little impact on power reqts.	Little, if any savings in non-consumables.	Little, if any savings in consumables required.
0 Worst Case	The proposal could increase power consumption.	Could increase non-consumable upmass requirements.	Could increase consumables upmass requirements.

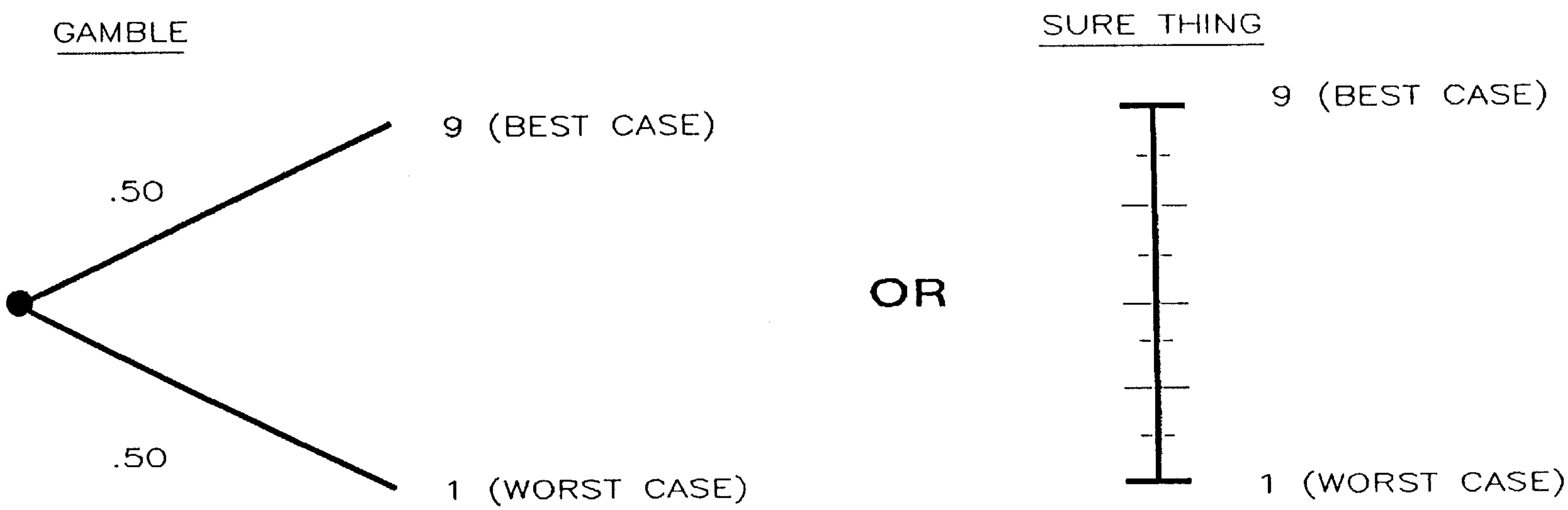
Attribute Scale for Growth Potential

Value	Scale Rating	Attribute Description
Best Case	10	Proposal would result in a large net improvement in SSF's ability to evolve or accept hooks and scars.
	7	Proposal would result in a moderate net improvement in SSF's ability to evolve or accept later upgrades.
	5	Proposal would result in no net change in SSF's ability to evolve or accept later upgrades.
	3	Proposal would result in minor negative net impacts on SSF's ability to evolve and accept later upgrades.
Worst Case	0	Proposal would result in some negative net impacts on SSF's ability to evolve and accept later upgrades.

Attribute Scale for Spinoff Potential

Value	Scale Rating	Attribute Description
Best Case	10	Proposal would have very high level of application to medium and low technology areas. Technologies will permeate into large markets (e.g., households).
	7	Proposal would have many applications. Automation activities are applicable to medium technology areas and usable for many areas of manufacturing and production.
	5	Proposal would yield some terrestrial applications. Main terrestrial examples are spinoffs to high technology applications such as computer software and manufacturing.
	3	Few terrestrial applications. Proposal developments are aimed at aerospace and military applications where costs are high and technology-specific (e.g., automated navigation and attitude control). Main terrestrial applications are spinoffs from SSF to other space applications such as unmanned satellites.
Worst Case	0	Little, if no terrestrial applications. All developments are SSF-specific and yield minimal technology transfer. Primary sources for transfer are documents describing developments and techniques. Few generalized methods or approaches to automation and robotics.

ATTRIBUTE: INITIAL COST



- FOR WHICH VALUE OF THE "SURE THING" ARE YOU INDIFFERENT BETWEEN THE "SURE THING" AND THE "GAMBLE"?

  INDIFFERENCE POINT ______

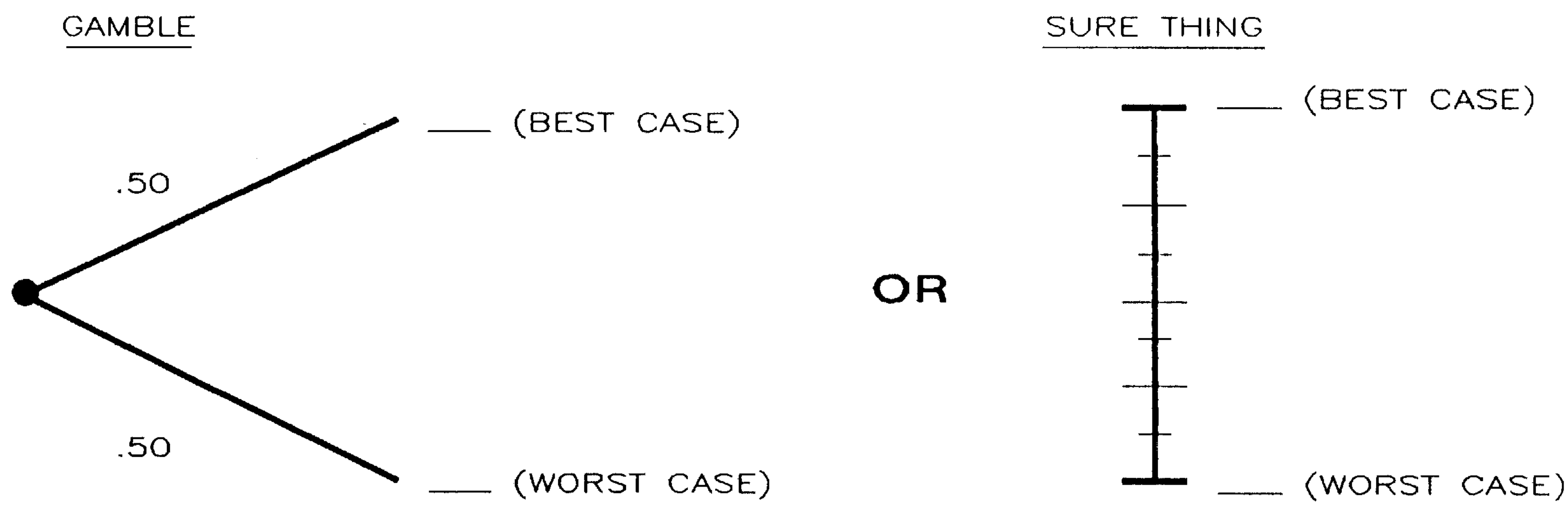
- IF YOU KNEW THAT ALL OTHER ATTRIBUTES WERE AT THEIR WORST STATES?

  INDIFFERENCE POINT ______

- IF YOU KNEW THAT ALL OTHER ATTRIBUTES WERE AT THEIR BEST STATES?

  INDIFFERENCE POINT ______

ATTRIBUTE: INITIAL COST



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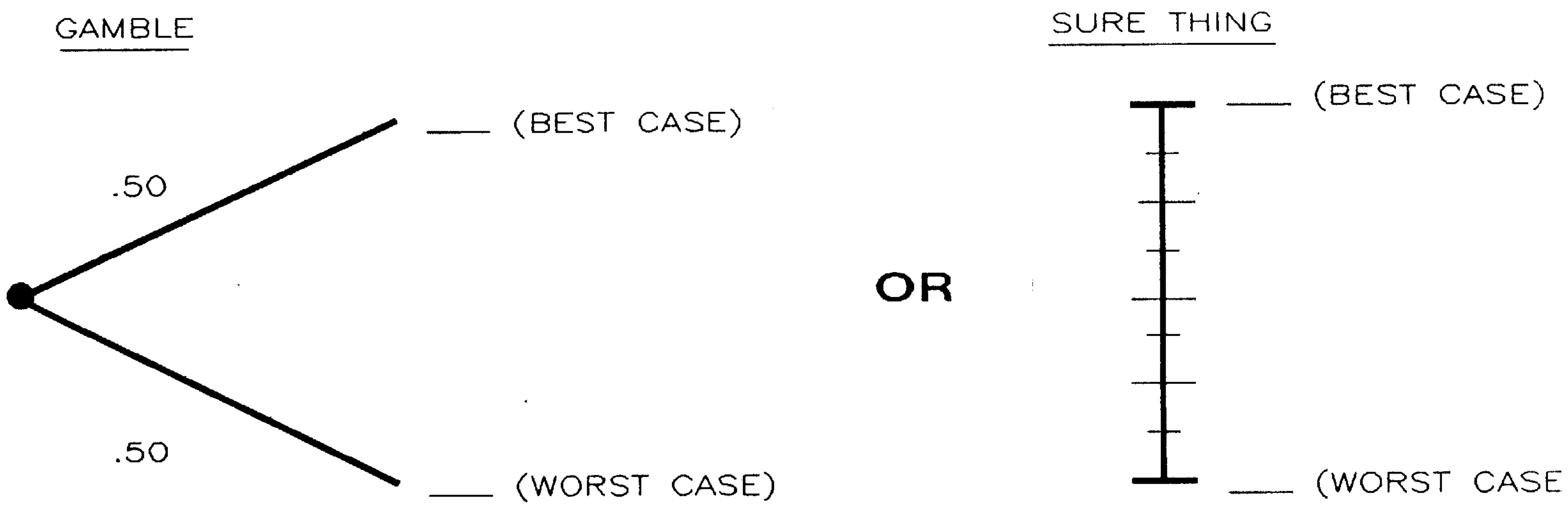
ATTRIBUTE: INITIAL COST



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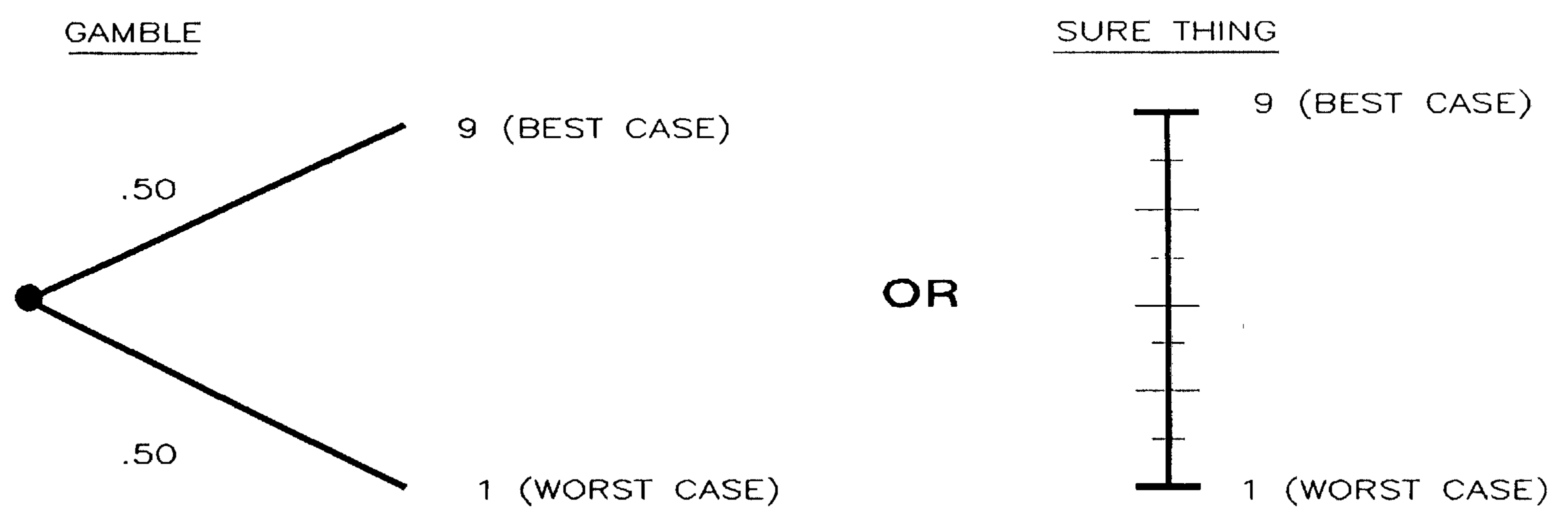
ATTRIBUTE: OPERATIONS COST IMPACTS



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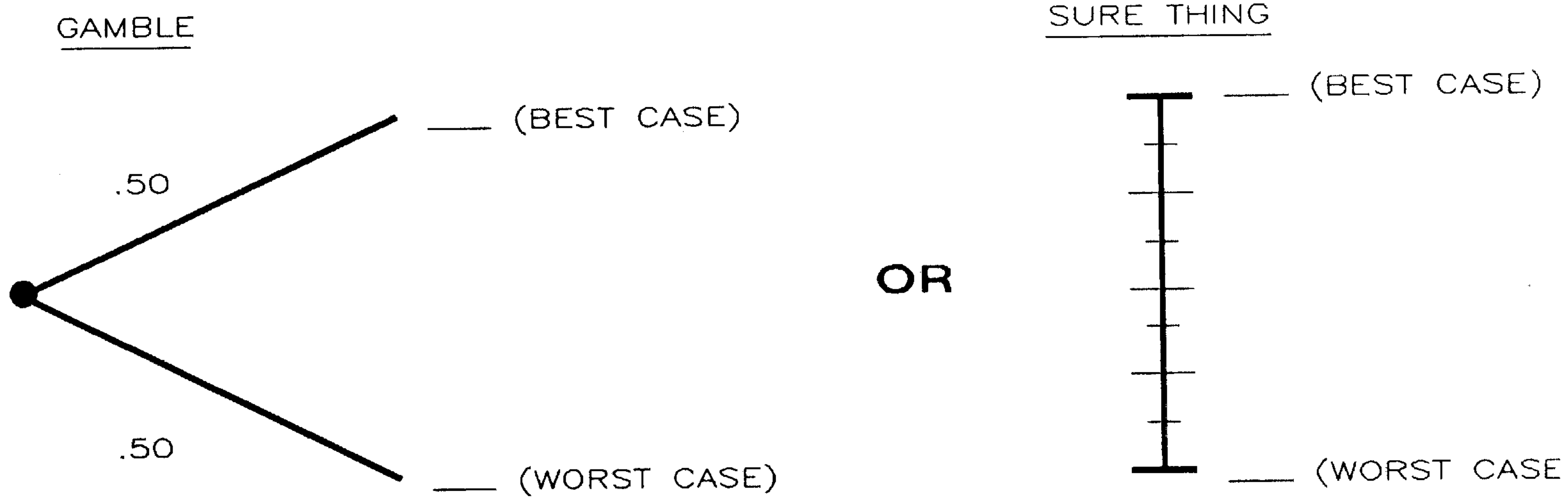
- **IF YOU KNEW THAT ALL OTHER ATTRIBUTES WERE AT THEIR BEST STATES?**

  INDIFFERENCE POINT ______

ATTRIBUTE: OPERATIONS COST



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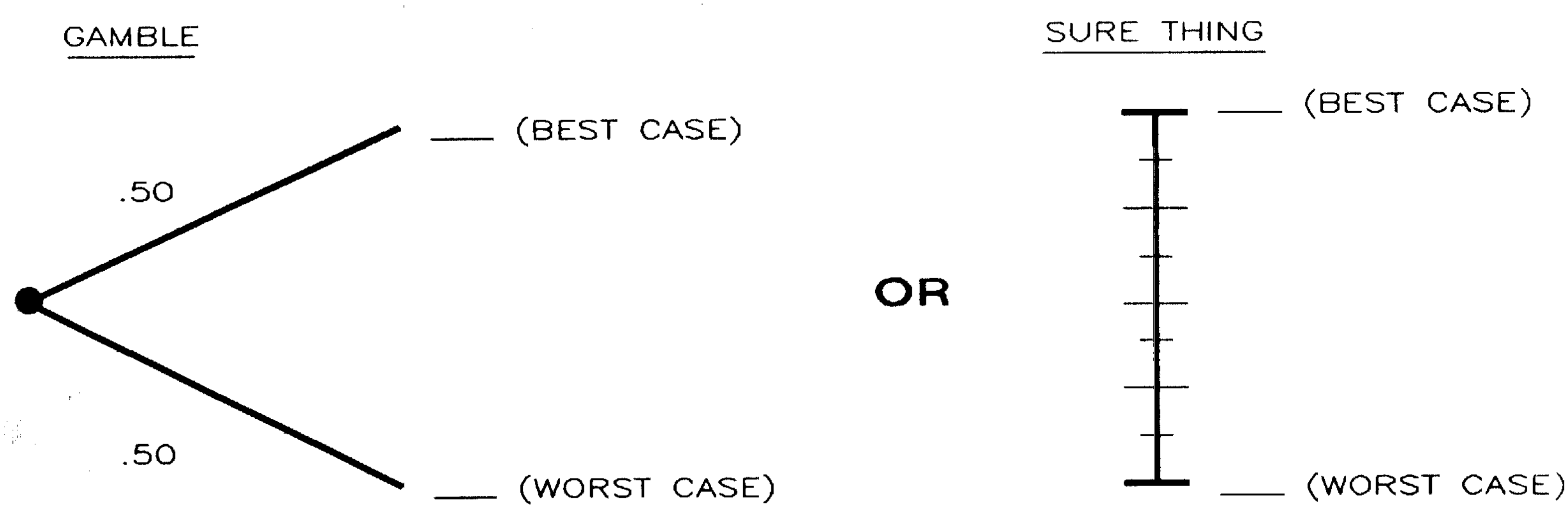
  INDIFFERENCE POINT ______

ATTRIBUTE: OPERATIONS COST



- **FOR WHICH VALUE OF THE "SURE THING" ARE YOU INDIFFERENT BETWEEN THE "SURE THING" AND THE "GAMBLE"?**

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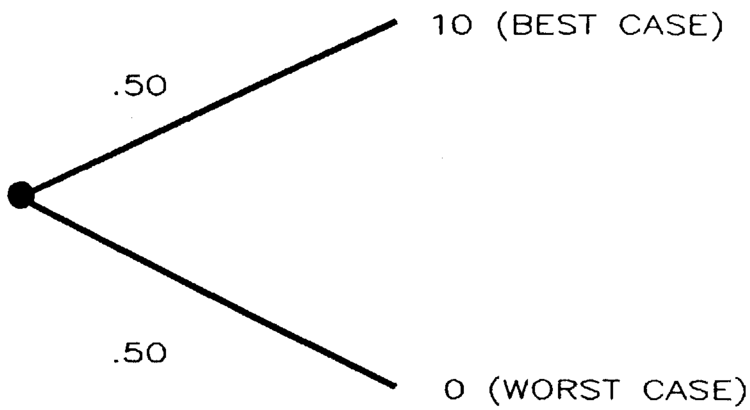
ATTRIBUTE: CREW PRODUCTIVITY

GAMBLE



OR

SURE THING

- **FOR WHICH VALUE OF THE "SURE THING" ARE YOU INDIFFERENT BETWEEN THE "SURE THING" AND THE "GAMBLE"?**

  INDIFFERENCE POINT ________

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- **IF YOU KNEW THAT ALL OTHER ATTRIBUTES WERE AT THEIR BEST STATES?**

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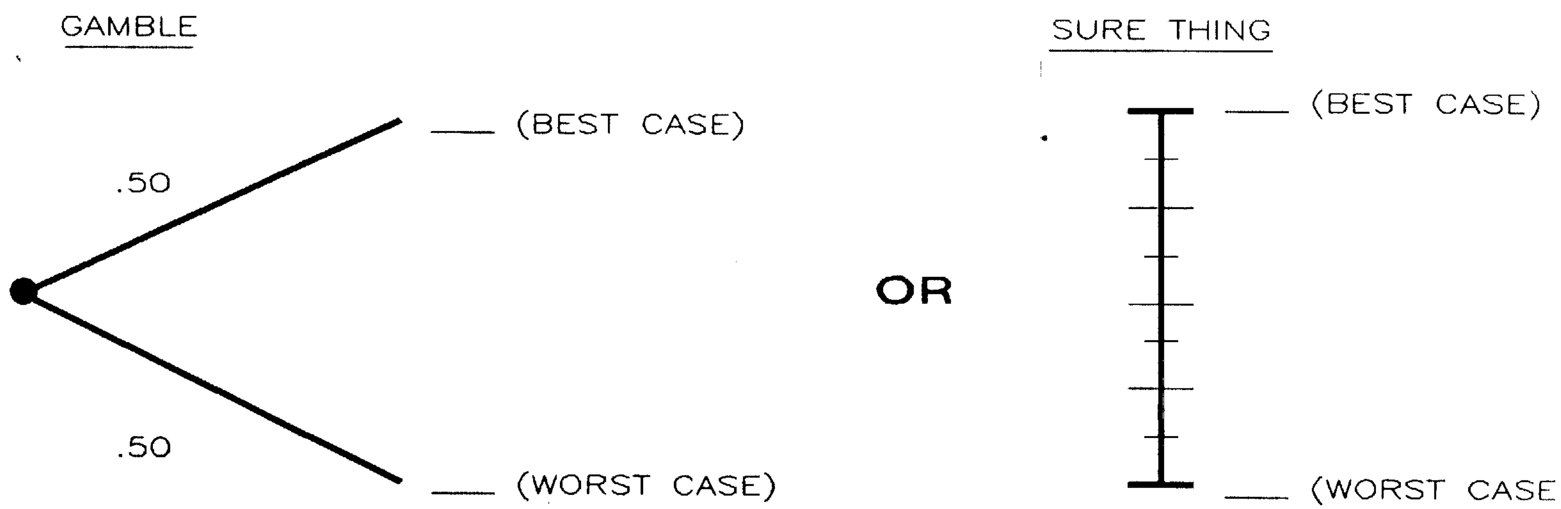
ATTRIBUTE: CREW PRODUCTIVITY



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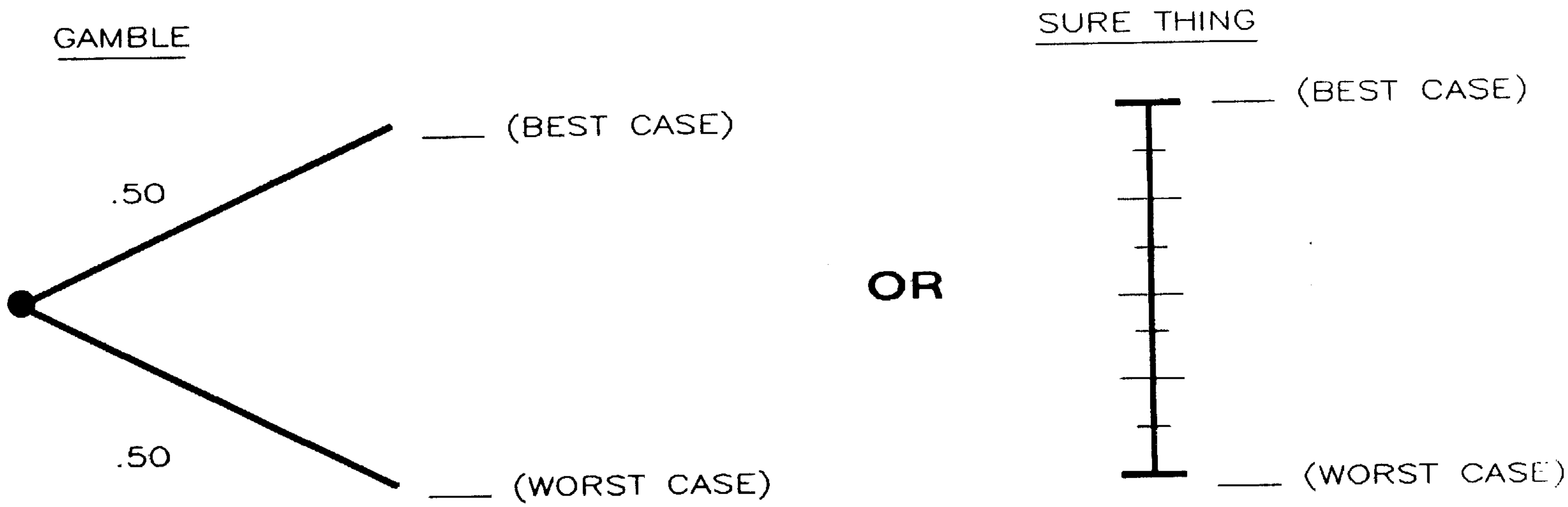
ATTRIBUTE: CREW PRODUCTIVITY



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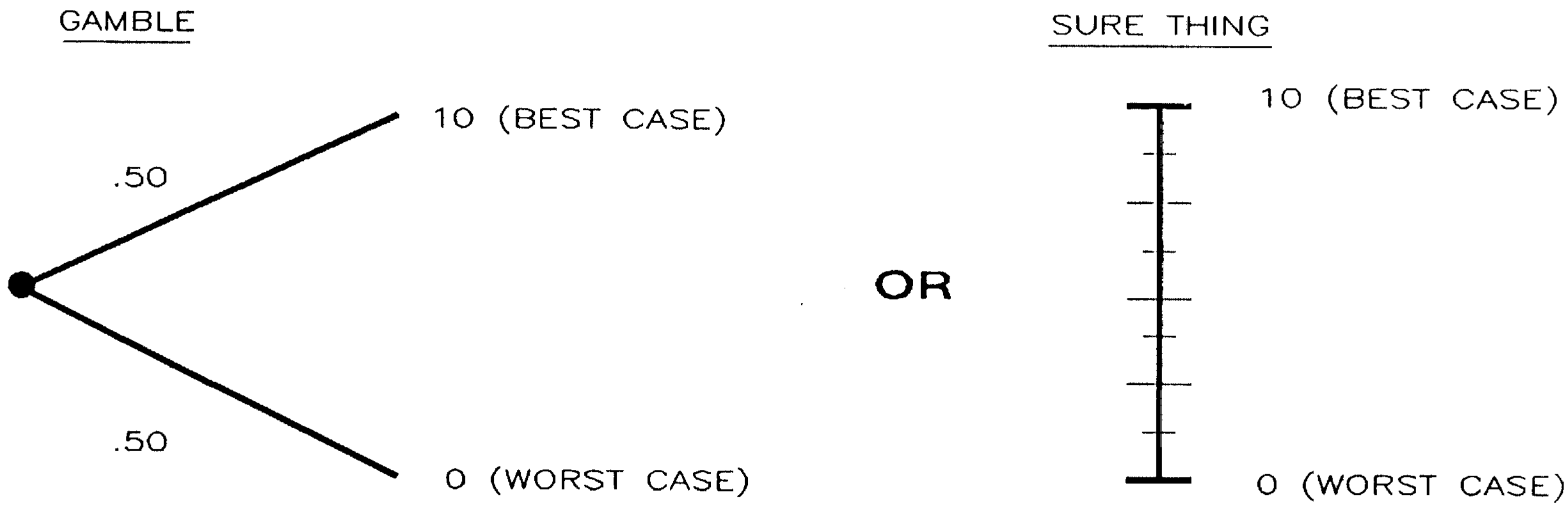
  INDIFFERENCE POINT ________

ATTRIBUTE: SAFETY



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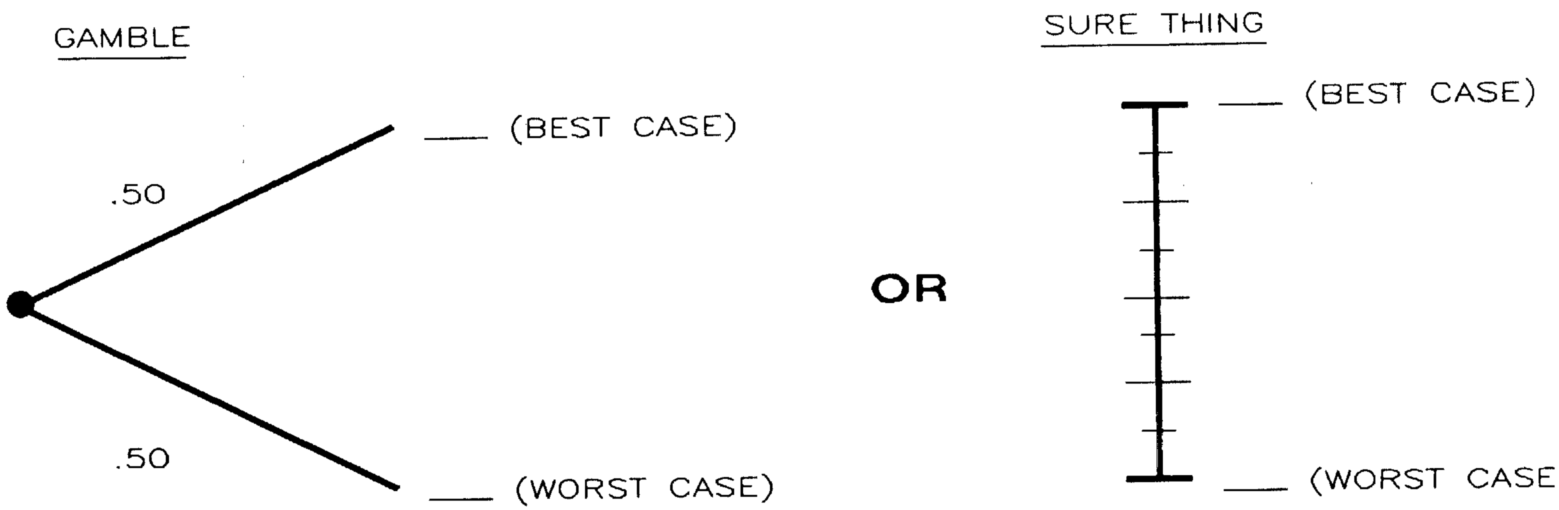
ATTRIBUTE: SAFETY



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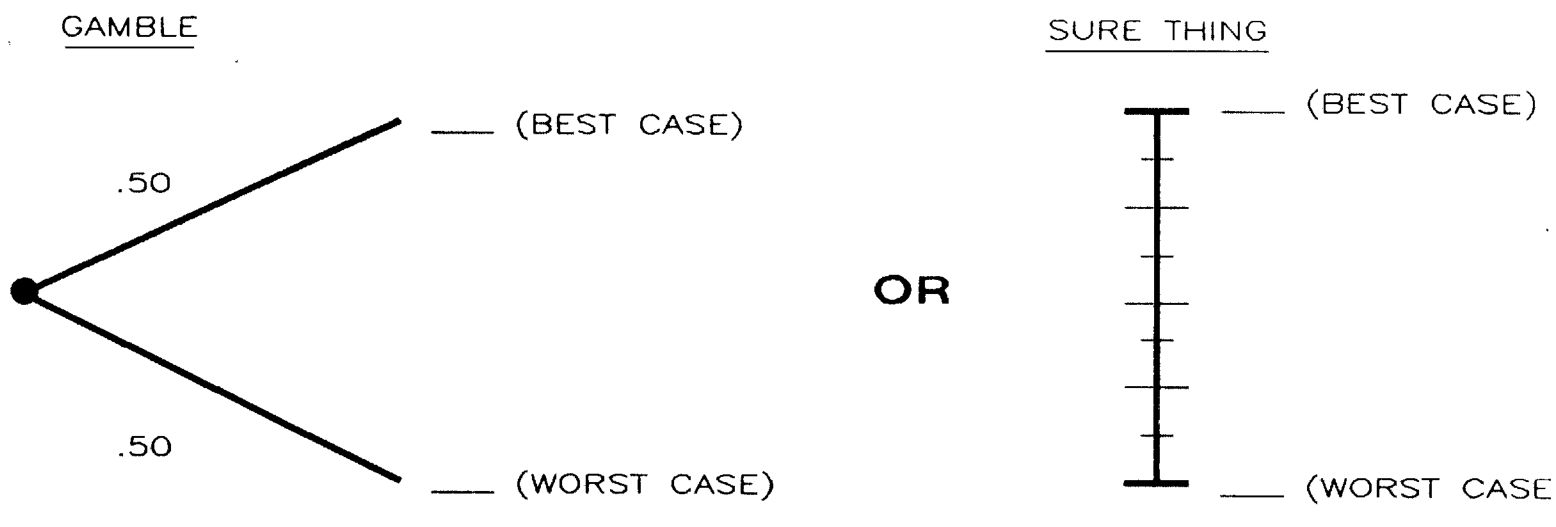
ATTRIBUTE: SAFETY



- **FOR WHICH VALUE OF THE "SURE THING" ARE YOU INDIFFERENT BETWEEN THE "SURE THING" AND THE "GAMBLE"?**

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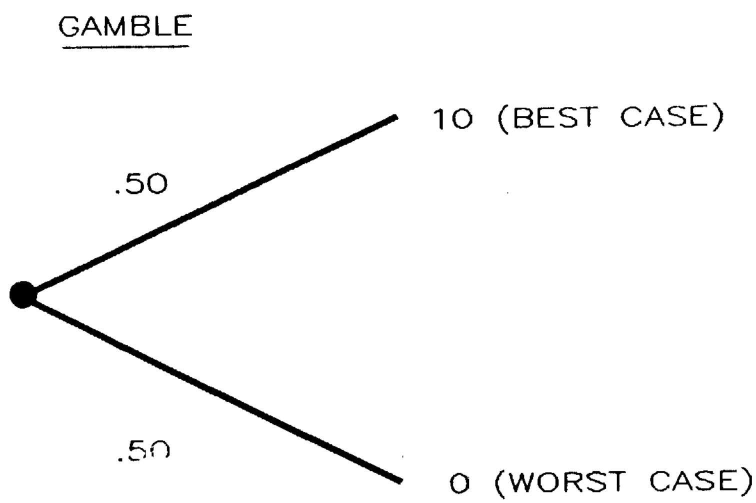
ATTRIBUTE: DEVELOPMENT RISK



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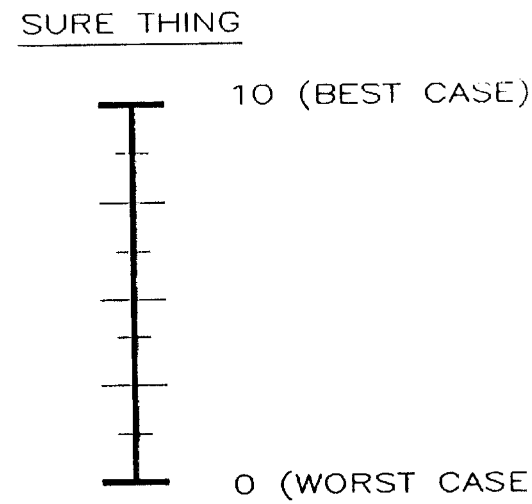

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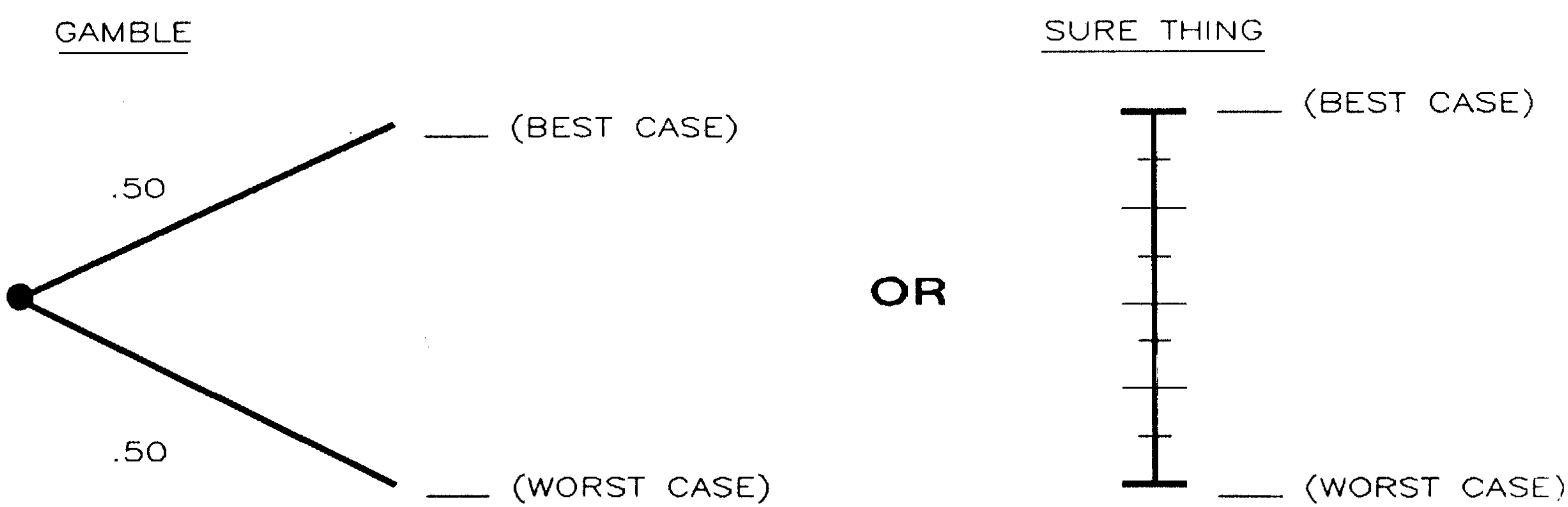
ATTRIBUTE: DEVELOPMENT RISK



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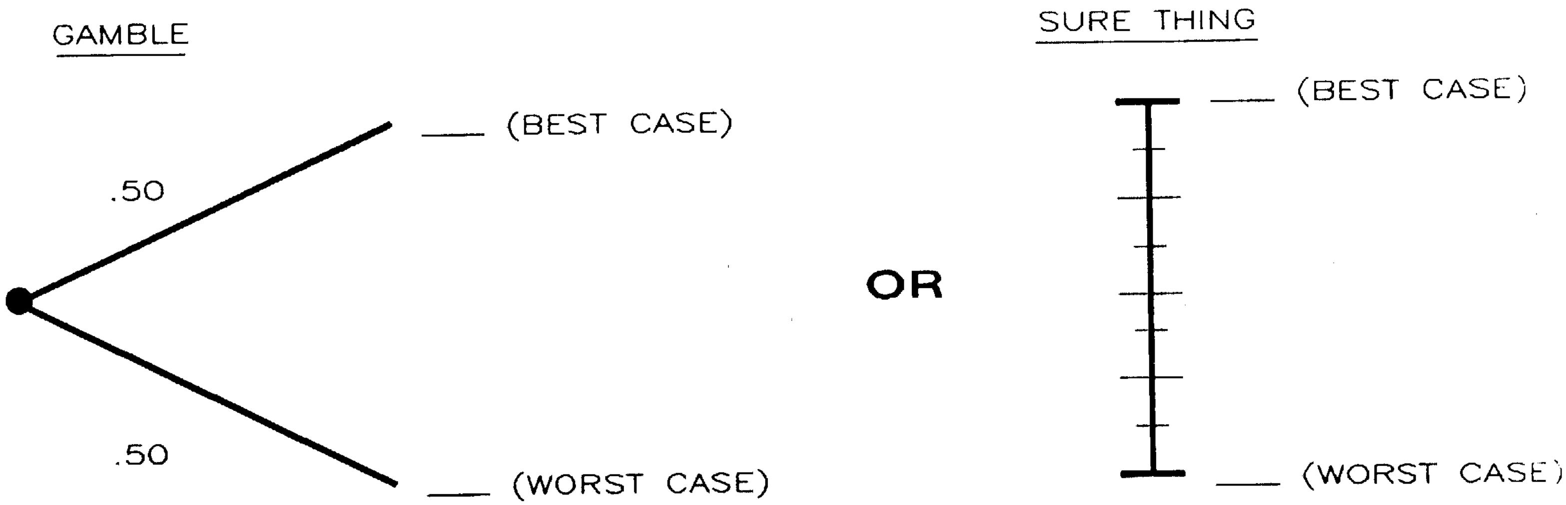
INDIFFERENCE POINT ______

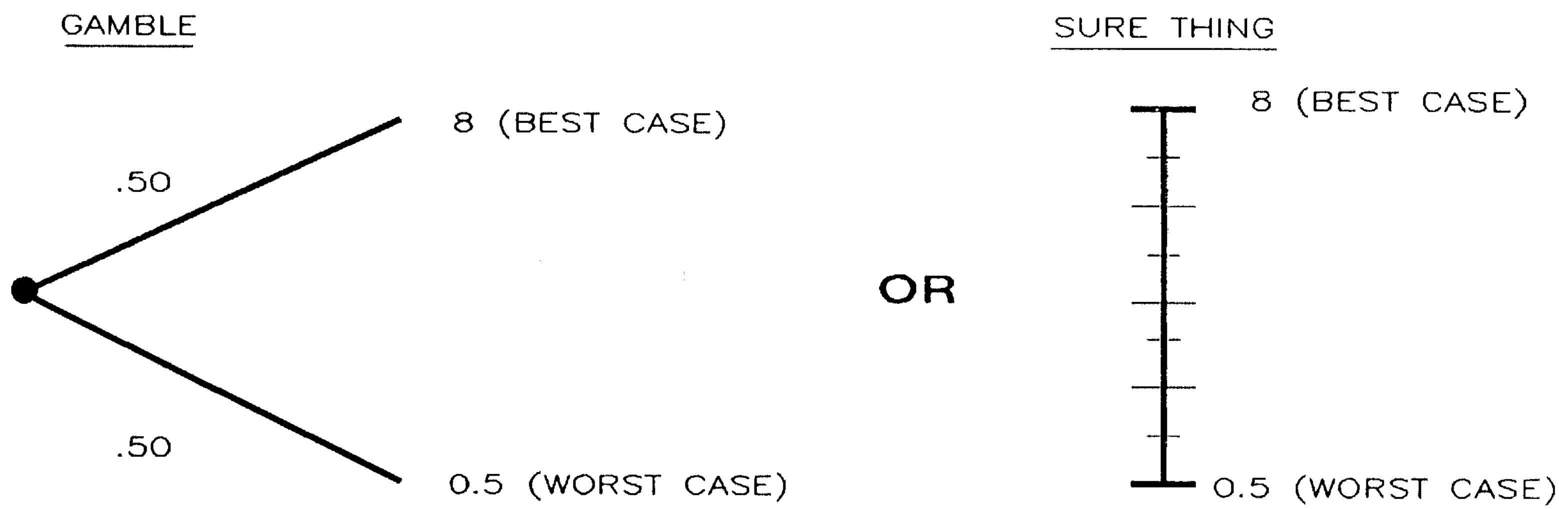
ATTRIBUTE: DEVELOPMENT RISK



- **FOR WHICH VALUE OF THE "SURE THING" ARE YOU INDIFFERENT BETWEEN THE "SURE THING" AND THE "GAMBLE"?**

  INDIFFERENCE POINT ________

ATTRIBUTE: RESOURCE REQUIREMENTS



- **FOR WHICH VALUE OF THE "SURE THING" ARE YOU INDIFFERENT BETWEEN THE "SURE THING" AND THE "GAMBLE"?**

  INDIFFERENCE POINT ______

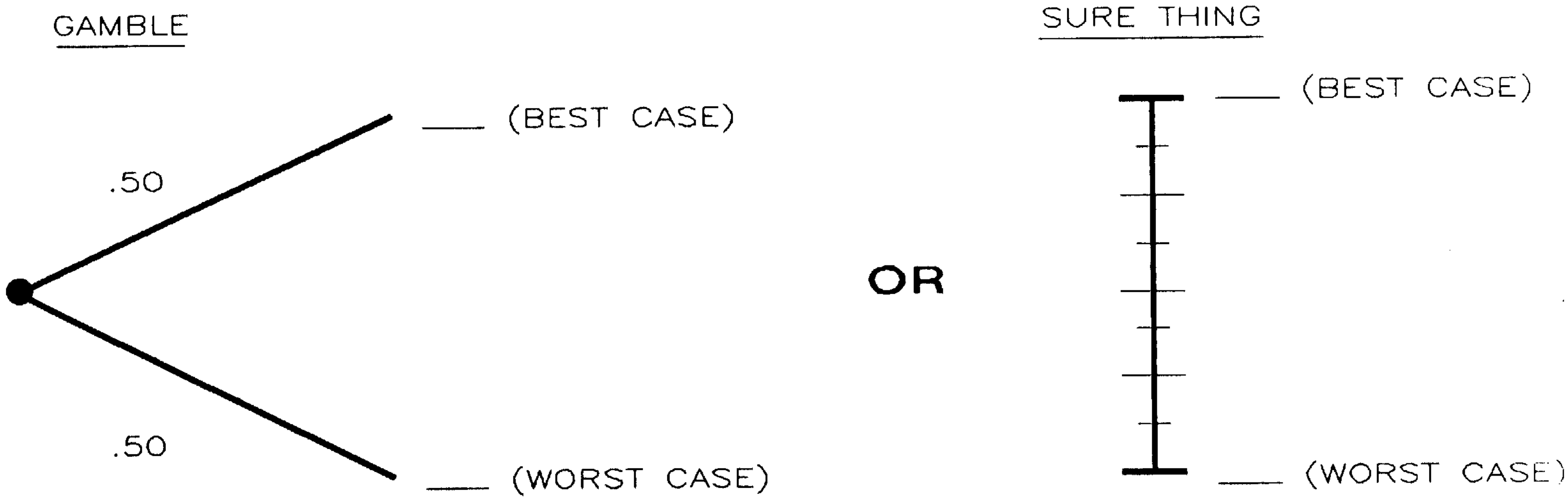
- **IF YOU KNEW THAT ALL OTHER ATTRIBUTES WERE AT THEIR WORST STATES?**

  INDIFFERENCE POINT ______

- **IF YOU KNEW THAT ALL OTHER ATTRIBUTES WERE AT THEIR BEST STATES?**

  INDIFFERENCE POINT ______

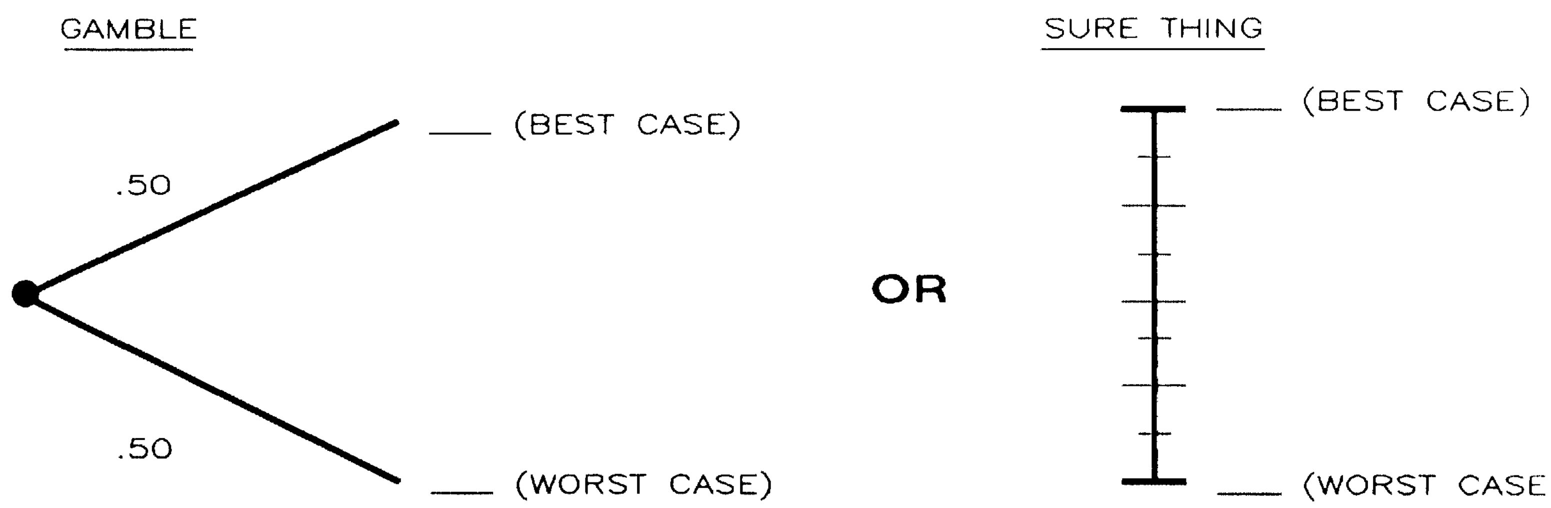
ATTRIBUTE: RESOURCE REQUIREMENTS



- **FOR WHICH VALUE OF THE "SURE THING" ARE YOU INDIFFERENT BETWEEN THE "SURE THING" AND THE "GAMBLE"?**

  INDIFFERENCE POINT ________

ATTRIBUTE: RESOURCE REQUIREMENTS

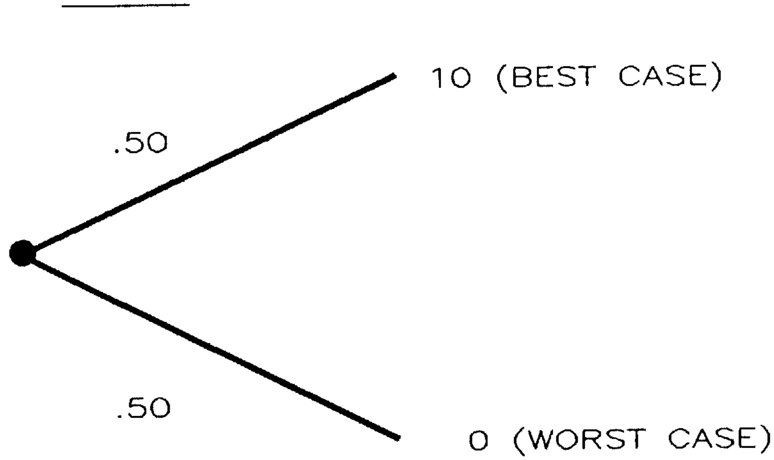


- **FOR WHICH VALUE OF THE "SURE THING" ARE YOU INDIFFERENT BETWEEN THE "SURE THING" AND THE "GAMBLE"?**

  INDIFFERENCE POINT _______

ATTRIBUTE: GROWTH POTENTIAL

GAMBLE



OR

SURE THING

- **FOR WHICH VALUE OF THE "SURE THING" ARE YOU INDIFFERENT BETWEEN THE "SURE THING" AND THE "GAMBLE"?**

  INDIFFERENCE POINT ________

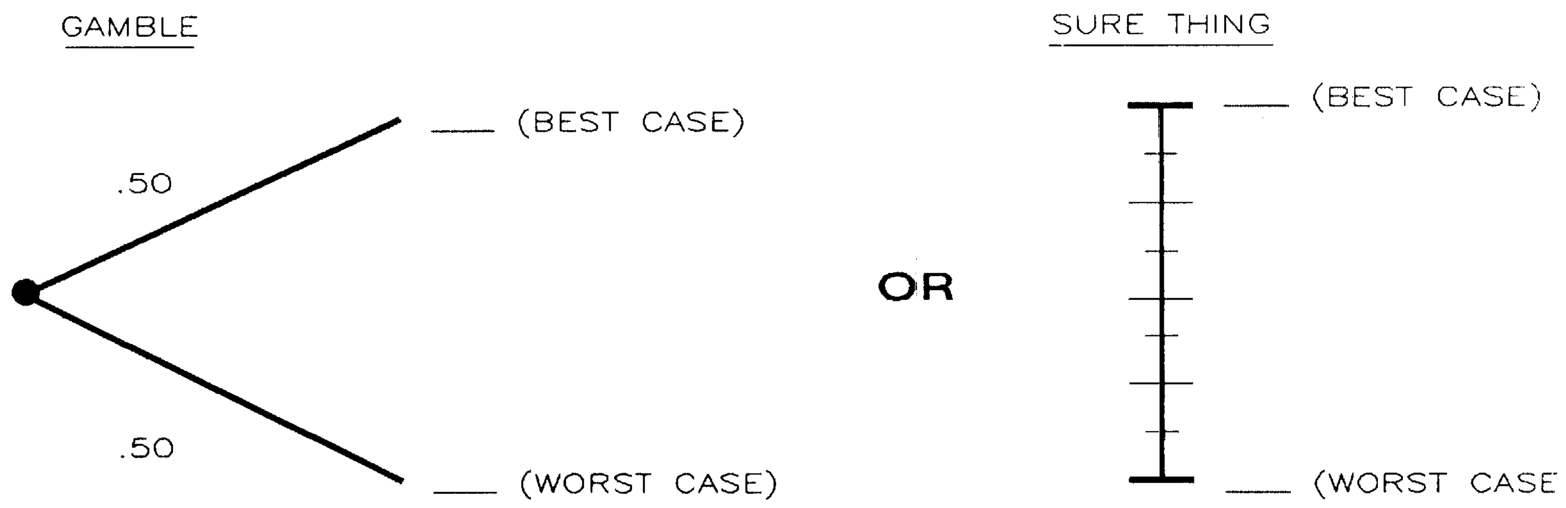
- **IF YOU KNEW THAT ALL OTHER ATTRIBUTES WERE AT THEIR WORST STATES?**

  INDIFFERENCE POINT ________

- **IF YOU KNEW THAT ALL OTHER ATTRIBUTES WERE AT THEIR BEST STATES?**

  INDIFFERENCE POINT ________

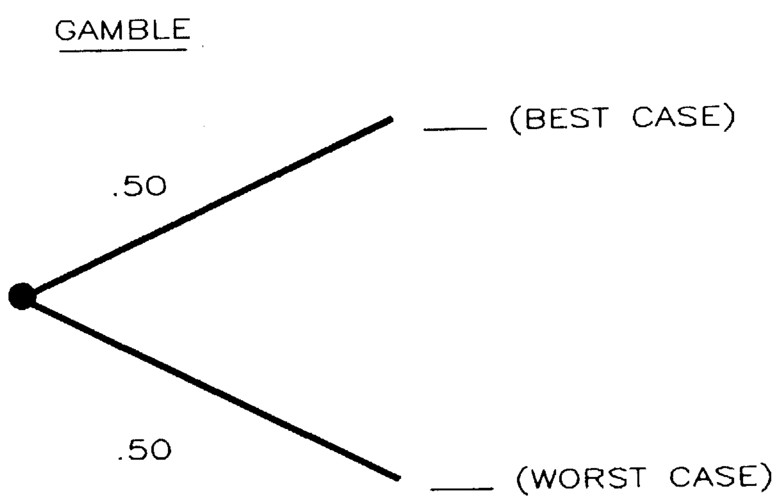
ATTRIBUTE: GROWTH POTENTIAL



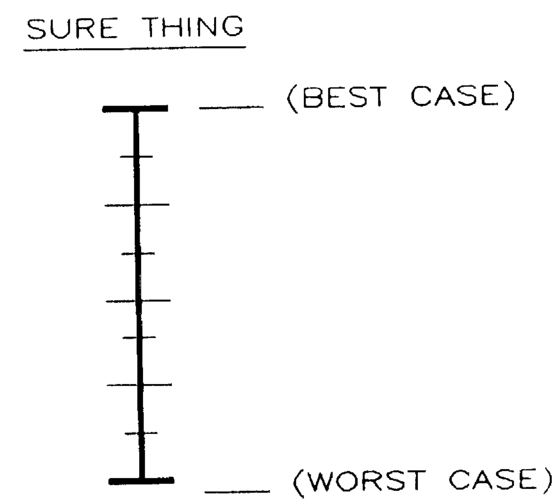
- **FOR WHICH VALUE OF THE "SURE THING" ARE YOU INDIFFERENT BETWEEN THE "SURE THING" AND THE "GAMBLE"?**

  INDIFFERENCE POINT ________

ATTRIBUTE: GROWTH POTENTIAL



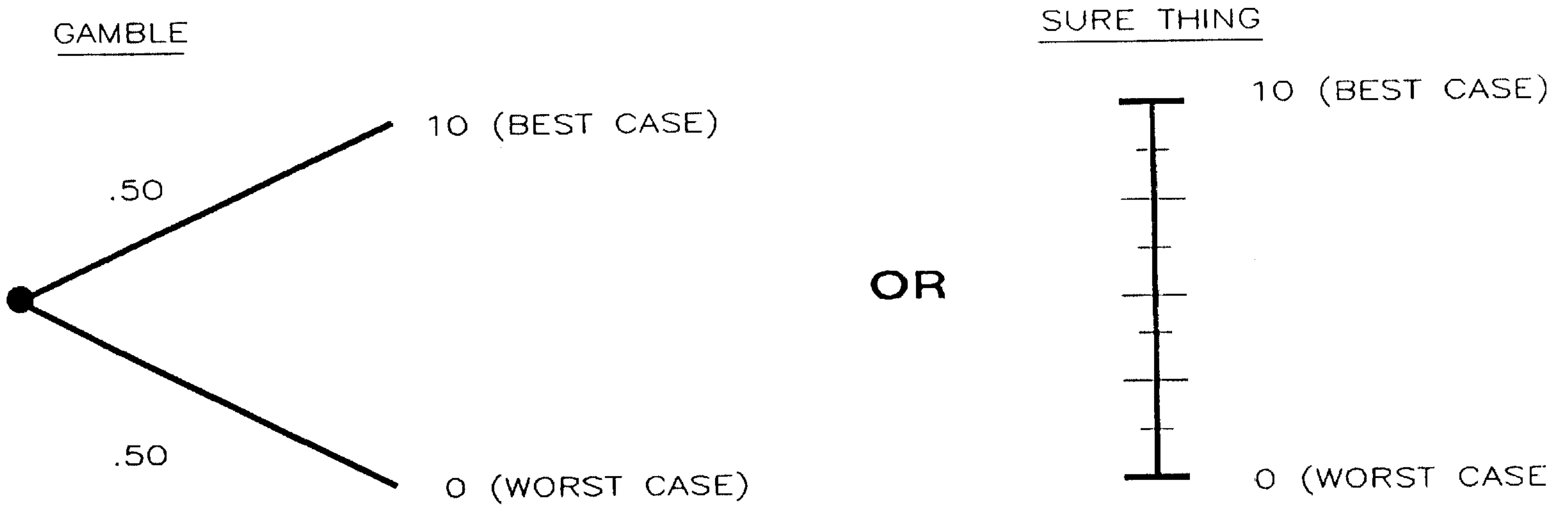
OR



- **FOR WHICH VALUE OF THE "SURE THING" ARE YOU INDIFFERENT BETWEEN THE "SURE THING" AND THE "GAMBLE"?**

INDIFFERENCE POINT ________

ATTRIBUTE: SPINOFF POTENTIAL



- **FOR WHICH VALUE OF THE "SURE THING" ARE YOU INDIFFERENT BETWEEN THE "SURE THING" AND THE "GAMBLE"?**

  INDIFFERENCE POINT ______

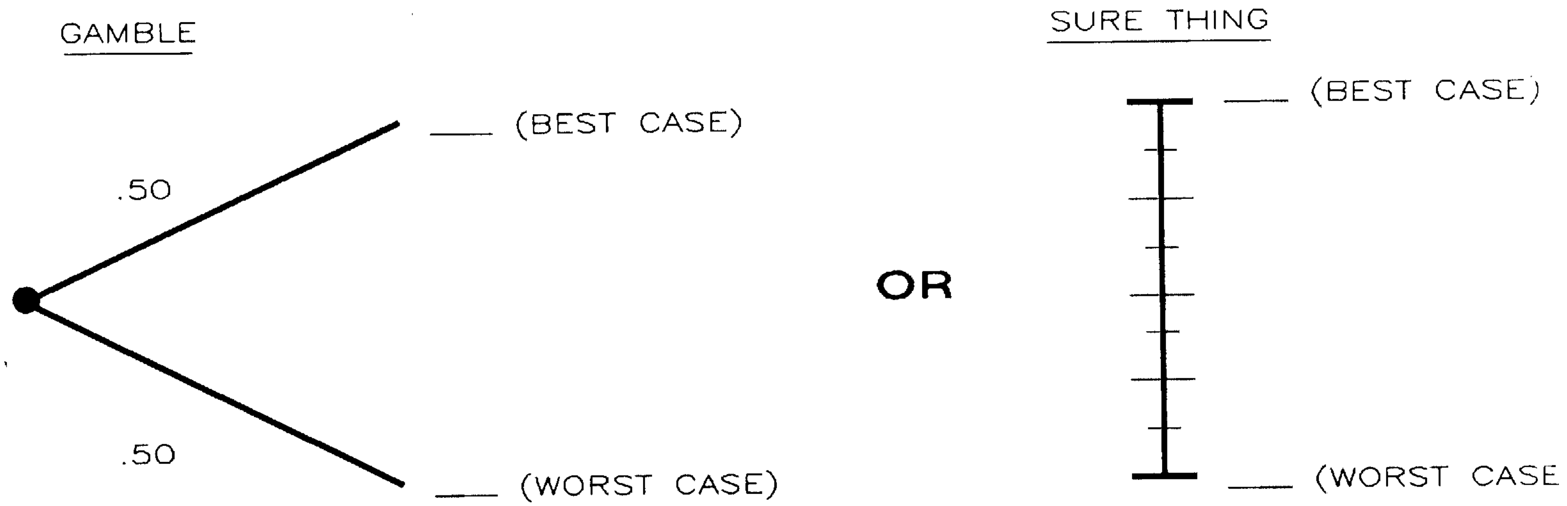
- **IF YOU KNEW THAT ALL OTHER ATTRIBUTES WERE AT THEIR WORST STATES?**

  INDIFFERENCE POINT ______

- **IF YOU KNEW THAT ALL OTHER ATTRIBUTES WERE AT THEIR BEST STATES?**

  INDIFFERENCE POINT ______

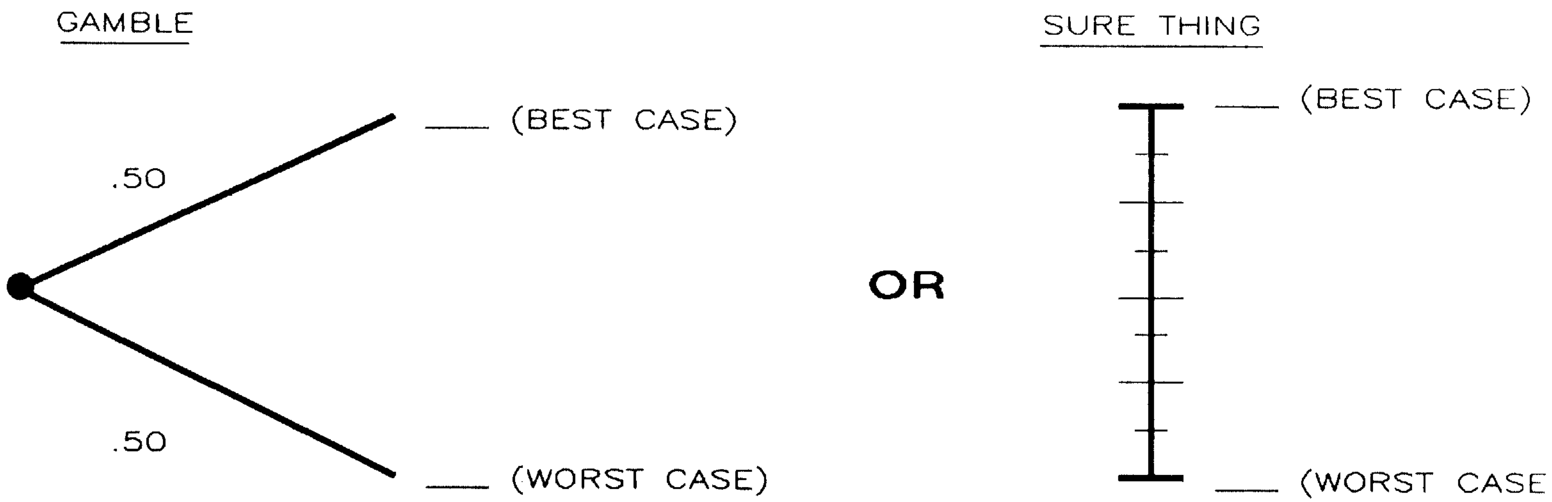
ATTRIBUTE: SPINOFF POTENTIAL



- **FOR WHICH VALUE OF THE "SURE THING" ARE YOU INDIFFERENT BETWEEN THE "SURE THING" AND THE "GAMBLE"?**

  INDIFFERENCE POINT ________

ATTRIBUTE: SPINOFF POTENTIAL



- **FOR WHICH VALUE OF THE "SURE THING" ARE YOU INDIFFERENT BETWEEN THE "SURE THING" AND THE "GAMBLE"?**

  INDIFFERENCE POINT ______

ORDER OF IMPORTANCE OF ATTRIBUTES

WHICH ATTRIBUTE WOULD YOU CHANGE FROM ITS WORST STATE TO ITS BEST STATE?

ATTRIBUTE	INITIAL COST	OPNS COST	CREW PROD.	SAFETY	DEVELOP. RISK	RESOURCE REQTS.	GROWTH POTENTIAL	SPINOFF POTENTIAL
BEST STATE								
WORST STATE								

ORDER OF IMPORTANCE								

ORDER OF IMPORTANCE OF ATTRIBUTES

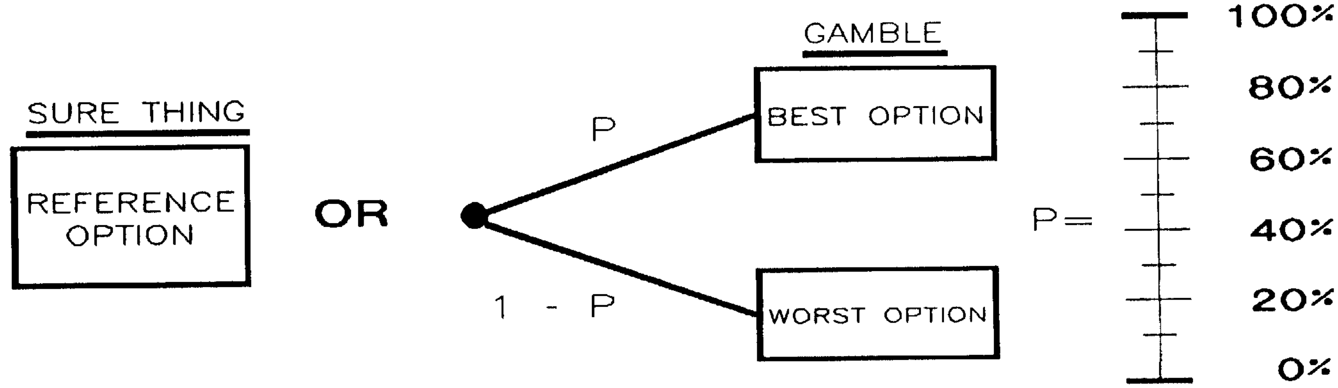
WHICH ATTRIBUTE WOULD YOU CHANGE FROM ITS WORST STATE TO ITS BEST STATE?

ATTRIBUTE	INITIAL COST	OPNS COST	CREW PROD.	SAFETY	DEVELOP. RISK	RESOURCE REQTS.	GROWTH POTENTIAL	SPINOFF POTENTIAL
BEST STATE	10	10	10	10	10	10	10	10
WORST STATE	0	0	0	0	0	0	0	0

ORDER OF IMPORTANCE								

IMPORTANCE OF: INITIAL COST

FOR WHAT VALUE OF P ARE YOU INDIFFERENT BETWEEN THE "SURE THING" AND THE "GAMBLE"?

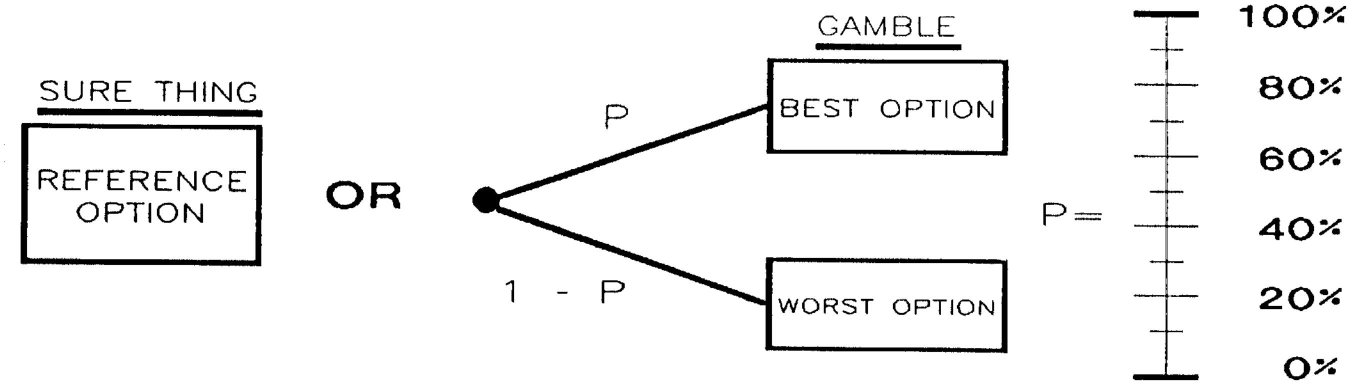


	INITIAL COST	OPERATIONS COST	CREW PROD.	SAFETY	DEVELOP. RISK	RESOURCE REQTS.	GROWTH POTENTIAL	SPINOFF POTENTIAL
REFERENCE OPTION:								
BEST OPTION:								
WORST OPTION:								

WHAT DO YOU WIN IF YOU WIN THE GAMBLE? WHAT DO YOU LOSE IF YOU LOSE THE GAMBLE?

IMPORTANCE OF: OPERATIONS COST

FOR WHAT VALUE OF P ARE YOU INDIFFERENT BETWEEN THE "SURE THING" AND THE "GAMBLE"?

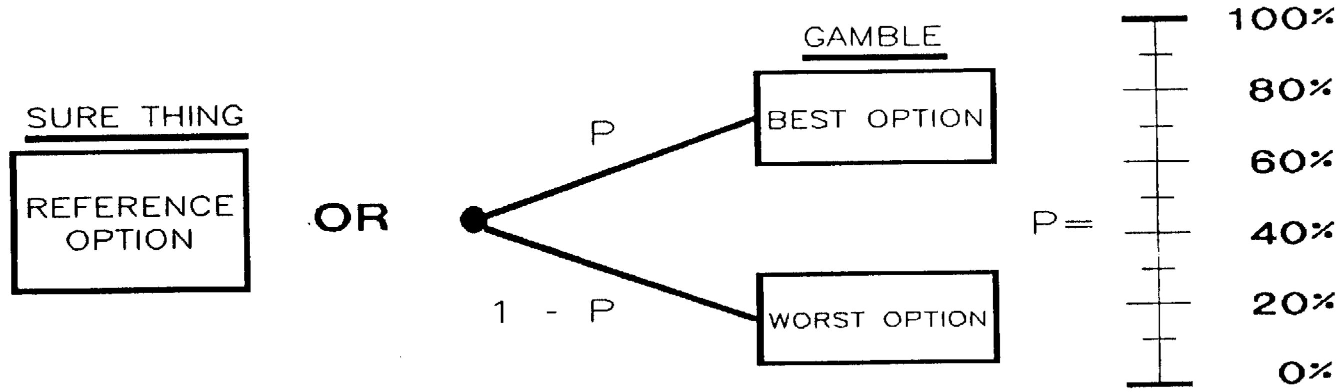


	INITIAL COST	OPERATIONS COST	CREW PROD.	SAFETY	DEVELOP. RISK	RESOURCE REQTS.	GROWTH POTENTIAL	SPINOFF POTENTIAL
REFERENCE OPTION:								
BEST OPTION:								
WORST OPTION:								

WHAT DO YOU WIN IF YOU WIN THE GAMBLE? WHAT DO YOU LOSE IF YOU LOSE THE GAMBLE?

IMPORTANCE OF: CREW PRODUCTIVITY

FOR WHAT VALUE OF P ARE YOU INDIFFERENT BETWEEN THE "SURE THING" AND THE "GAMBLE"?

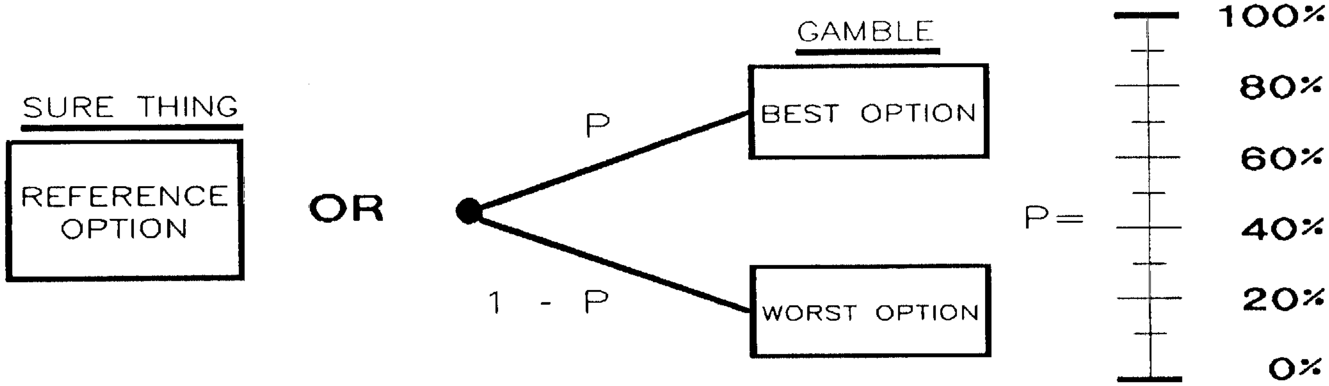


	INITIAL COST	OPERATIONS COST	CREW PROD.	SAFETY	DEVELOP. RISK	RESOURCE REQTS.	GROWTH POTENTIAL	SPINOFF POTENTIAL
REFERENCE OPTION:								
BEST OPTION:								
WORST OPTION:								

WHAT DO YOU WIN IF YOU WIN THE GAMBLE? WHAT DO YOU LOSE IF YOU LOSE THE GAMBLE?

IMPORTANCE OF: SAFETY

FOR WHAT VALUE OF P ARE YOU INDIFFERENT BETWEEN THE "SURE THING" AND THE "GAMBLE"?

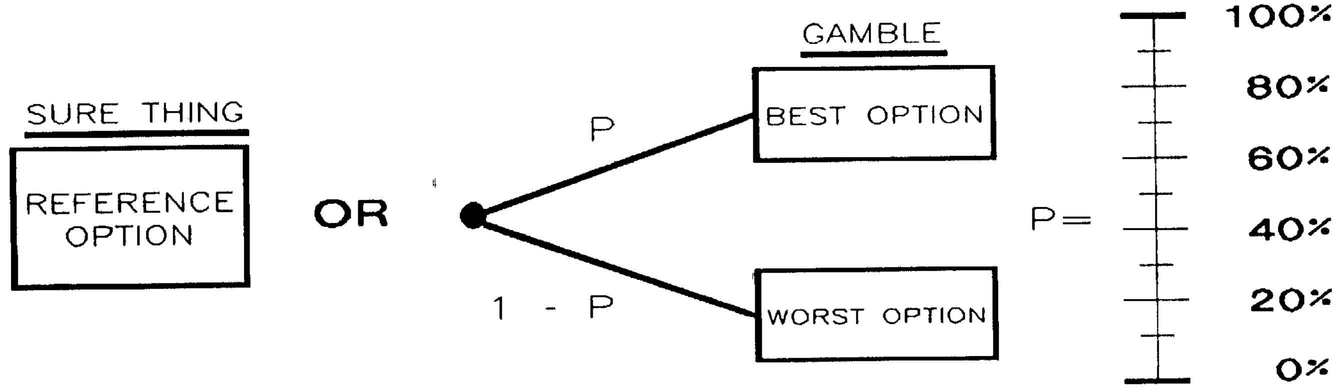


	INITIAL COST	OPERATIONS COST	CREW PROD.	SAFETY	DEVELOP. RISK	RESOURCE REQTS.	GROWTH POTENTIAL	SPINOFF POTENTIAL
REFERENCE OPTION:								
BEST OPTION:								
WORST OPTION:								

WHAT DO YOU WIN IF YOU WIN THE GAMBLE? WHAT DO YOU LOSE IF YOU LOSE THE GAMBLE?

IMPORTANCE OF: DEVELOPMENT RISK

FOR WHAT VALUE OF P ARE YOU INDIFFERENT BETWEEN THE "SURE THING" AND THE "GAMBLE"?

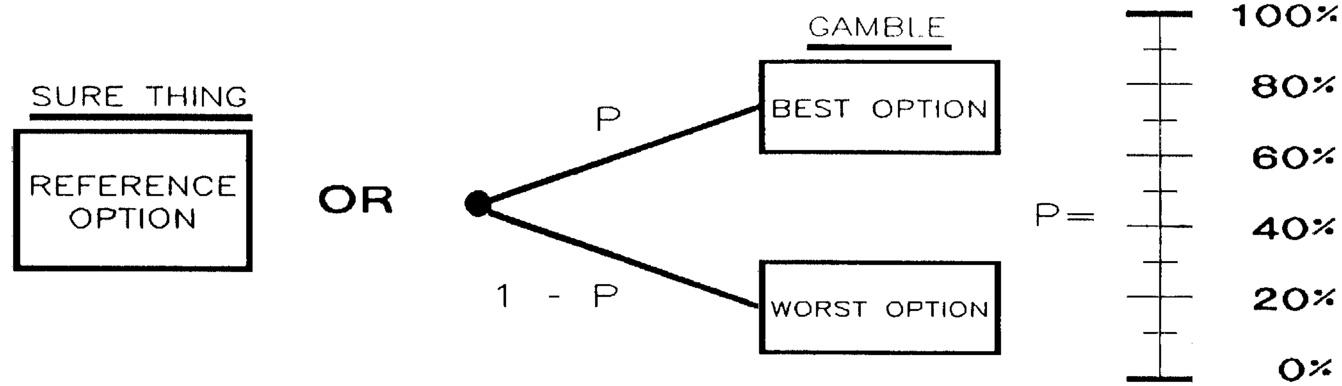


	INITIAL COST	OPERATIONS COST	CREW PROD.	SAFETY	DEVELOP. RISK	RESOURCE REQTS.	GROWTH POTENTIAL	SPINOFF POTENTIAL
REFERENCE OPTION:								
BEST OPTION:								
WORST OPTION:								

WHAT DO YOU WIN IF YOU WIN THE GAMBLE? WHAT DO YOU LOSE IF YOU LOSE THE GAMBLE?

IMPORTANCE OF: RESOURCE CONSTRAINTS

FOR WHAT VALUE OF P ARE YOU INDIFFERENT BETWEEN THE "SURE THING" AND THE "GAMBLE"?

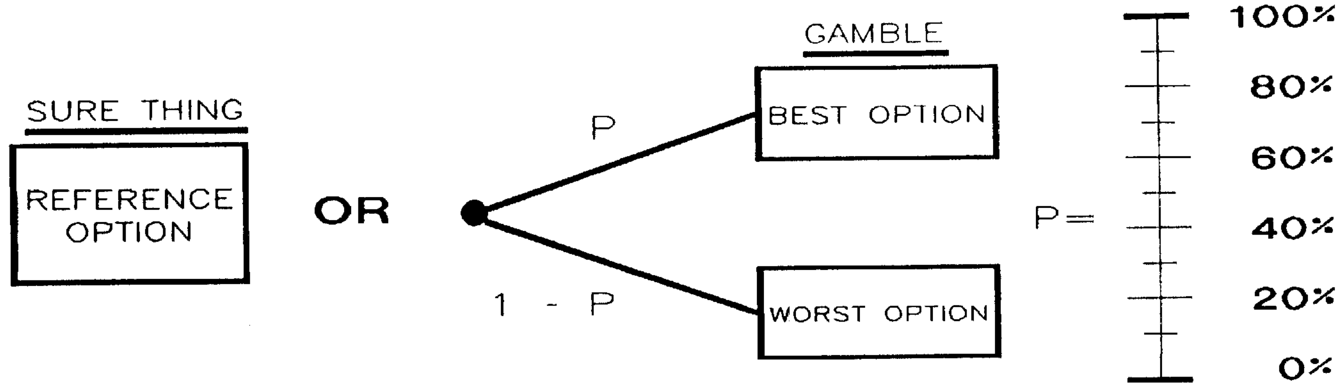


	INITIAL COST	OPERATIONS COST	CREW PROD.	SAFETY	DEVELOP. RISK	RESOURCE REQTS.	GROWTH POTENTIAL	SPINOFF POTENTIAL
REFERENCE OPTION:								
BEST OPTION:								
WORST OPTION:								

WHAT DO YOU WIN IF YOU WIN THE GAMBLE? WHAT DO YOU LOSE IF YOU LOSE THE GAMBLE?

IMPORTANCE OF: GROWTH POTENTIAL

FOR WHAT VALUE OF P ARE YOU INDIFFERENT BETWEEN THE "SURE THING" AND THE "GAMBLE"?

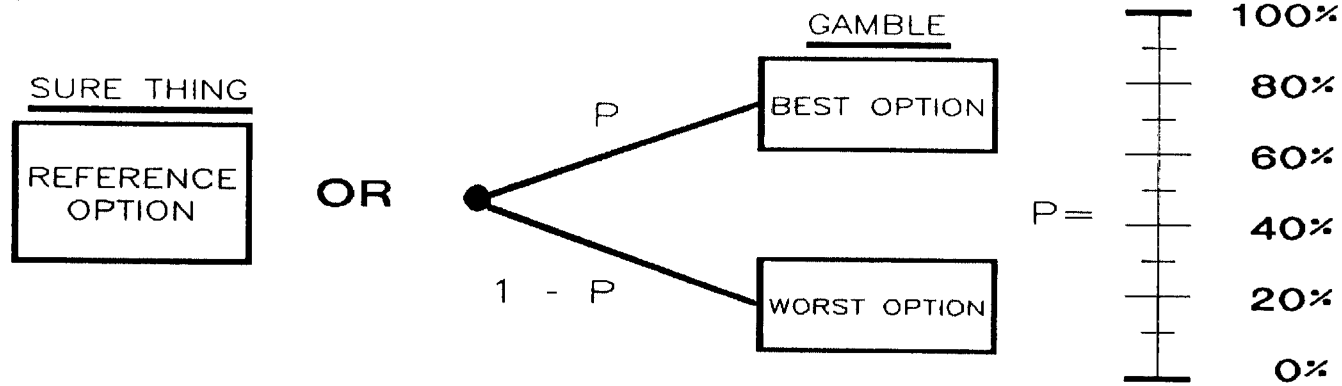


	INITIAL COST	OPERATIONS COST	CREW PROD.	SAFETY	DEVELOP. RISK	RESOURCE REQTS.	GROWTH POTENTIAL	SPINOFF POTENTIAL
REFERENCE OPTION:								
BEST OPTION:								
WORST OPTION:								

WHAT DO YOU WIN IF YOU WIN THE GAMBLE? WHAT DO YOU LOSE IF YOU LOSE THE GAMBLE?

IMPORTANCE OF: SPINOFF POTENTIAL

FOR WHAT VALUE OF P ARE YOU INDIFFERENT BETWEEN THE "SURE THING" AND THE "GAMBLE"?



	INITIAL COST	OPERATIONS COST	CREW PROD.	SAFETY	DEVELOP. RISK	RESOURCE REQTS.	GROWTH POTENTIAL	SPINOFF POTENTIAL
REFERENCE OPTION:								
BEST OPTION:								
WORST OPTION:								

WHAT DO YOU WIN IF YOU WIN THE GAMBLE? WHAT DO YOU LOSE IF YOU LOSE THE GAMBLE?

APPENDIX C

DECISION MODEL CASES AND SAMPLE COMPUTER OUTPUT FOR SENSITIVITY ANALYSIS

Table C-1. Decision Model Sensitivity Analysis Cases[1]

OUTPUT FILENAME	DECISION MODEL OPTIONS	CASE NUMBER
Original Baseline Disk Input File		
HLEV000	DET/A/NOM/PRIM/MULT	0
Deterministic Baseline-Nominal Case		
HLEV001 Group 1	DET/1/NOM/PRIM/MULT	1
HLEV002 Group 2	DET/2/NOM/PRIM/MULT	2
HLEV003 Group 3	DET/3/NOM/PRIM/MULT	3
HLEV004 Group All	DET/A/NOM/PRIM/MULT	4
Probabilistic Baseline-Nominal Case		
HLEV011 Group 1	PROB/1/NOM/PRIM/MULT	5
HLEV012 Group 2	PROB/2/NOM/PRIM/MULT	6
HLEV013 Group 3	PROB/3/NOM/PRIM/MULT	7
HLEV014 Group All	PROB/A/NOM/PRIM/MULT	8
Deterministic Baseline-Best Case		
HLEV051 Group 1	DET/1/BEST/PRIM/MULT	9
HLEV052 Group 2	DET/2/BEST/PRIM/MULT	10
HLEV053 Group 3	DET/3/BEST/PRIM/MULT	11
HLEV054 Group All	DET/A/BEST/PRIM/MULT	12
Deterministic Baseline-Worst Case		
HLEV061 Group 1	DET/1/WORST/PRIM/MULT	13
HLEV062 Group 2	DET/2/WORST/PRIM/MULT	14
HLEV063 Group 3	DET/3/WORST/PRIM/MULT	15
HLEV064 Group All	DET/A/WORST/PRIM/MULT	16

[1] The potential number of cases to be examined is:

Analysis Mode	2:	Deterministic (DET); Probabilistic (PROB).
Number of cases	4:	groups composed of interested parties 1,2,3, and (A)LL.
Attribute state assumptions	3:	Nominal states (NOM), Best Case attribute states, (BEST), and Worst Case attribute states (WORST).
Attribute data estimates	1:	One primary data set analyzed (PRIM)
Decision models	x 2:	Multiplicative Model (MULT); Additive Model (ADD).
	= 48 combinations	

Table C-1. Decision Model Sensitivity Analysis Cases (Continued)

OUTPUT FILENAME	DECISION MODEL OPTIONS	CASE NUMBER
Probabilistic Baseline-Best Case		
HLEV021 Group 1	PROB/1/BEST/PRIM/MULT	17
HLEV022 Group 2	PROB/2/BEST/PRIM/MULT	18
HLEV023 Group 3	PROB/3/BEST/PRIM/MULT	19
HLEV024 Group All	PROB/A/BEST/PRIM/MULT	20
Probabilistic Baseline-Worst Case		
HLEV031 Group 1	PROB/1/WORST/PRIM/MULT	21
HLEV032 Group 2	PROB/2/WORST/PRIM/MULT	22
HLEV033 Group 3	PROB/3/WORST/PRIM/MULT	23
HLEV034 Group All	PROB/A/WORST/PRIM/MULT	24
Deterministic Baseline-Nominal Case		
Checks differences between decision models		
HLEV111 Group 1	DET/1/NOM/PRIM/ADD	25
HLEV112 Group 2	DET/2/NOM/PRIM/ADD	26
HLEV113 Group 3	DET/3/NOM/PRIM/ADD	27
HLEV114 Group All	DET/A/NOM/PRIM/ADD	28
Probabilistic Baseline-Nominal Case		
Checks differences between decision models		
HLEV041 Group 1	PROB/1/NOM/PRIM/ADD	29
HLEV042 Group 2	PROB/2/NOM/PRIM/ADD	30
HLEV043 Group 3	PROB/3/NOM/PRIM/ADD	31
HLEV044 Group All	PROB/A/NOM/PRIM/ADD	32
Deterministic Baseline-Best Case		
Checks differences between decision models		
HLEV071 Group 1	DET/1/BEST/PRIM/ADD	33
HLEV072 Group 2	DET/2/BEST/PRIM/ADD	34
HLEV073 Group 3	DET/3/BEST/PRIM/ADD	35
HLEV074 Group All	DET/A/BEST/PRIM/ADD	36
Deterministic Baseline-Worst Case		
Checks differences between decision models		
HLEV081 Group 1	DET/1/WORST/PRIM/ADD	37
HLEV082 Group 2	DET/2/WORST/PRIM/ADD	38
HLEV083 Group 3	DET/3/WORST/PRIM/ADD	39
HLEV084 Group All	DET/A/WORST/PRIM/ADD	40

Table C-1. Decision Model Sensitivity Analysis Cases (Continued)

OUTPUT FILENAME	DECISION MODEL OPTIONS	CASE NUMBER
Probabilistic Baseline-Best Case		
HLEV091 Group 1	PROB/1/BEST/PRIM/ADD	41
HLEV092 Group 2	PROB/2/BEST/PRIM/ADD	42
HLEV093 Group 3	PROB/3/BEST/PRIM/ADD	43
HLEV094 Group All	PROB/A/BEST/PRIM/ADD	44
Probabilistic Baseline-Worst Case		
Checks differences between decision models		
HLEV101 Group 1	PROB/1/WORST/PRIM/ADD	45
HLEV102 Group 2	PROB/2/WORST/PRIM/ADD	46
HLEV103 Group 3	PROB/3/WORST/PRIM/ADD	47
HLEV104 Group All	PROB/A/WORST/PRIM/ADD	48

SUMMARY REPORT
FOR CASE: HLEV000

This report summarizes the results of HLEV000 as follows:

I Introduction and Case Specifications

A. The Alternatives
B. The Attributes
C. The Decision Makers
D. The Analysis Mode
E. The Run Option
F. The Decision Model

II Individual Decision Maker Rankings

III Decision Maker Rankings As a Group

IV Appendices

A. The Attribute State/Distribution Inputs
B. The Preference Inputs for Each Decision Maker

SECTION I
INTRODUCTION AND CASE SPECIFICATIONS

This Section presents the specifications for the decision making case defined.

A. The Alternatives are:
Alternative 1 = FAULTPRED
Alternative 2 = PROTOSCHED
Alternative 3 = EXTFAULTTB
Alternative 4 = KBSFAULTRE
Alternative 5 = VDDTOMADMS
Alternative 6 = ACCELSSMPM
Alternative 7 = A&RPROTOTY
Alternative 8 = DIAGES/EPS
Alternative 9 = ABDUCT/EPS
Alternative 10 = STD/TLS/ES
Alternative 11 = AUTROBASSY
Alternative 12 = TRTHERMPOS
Alternative 13 = EVARETRIEV
Alternative 14 = AUTROBSIM
Alternative 15 = STEREOTELE
Alternative 16 = WORLDMODEL
Alternative 17 = ROBCTLASSY
Alternative 18 = KNOWACQSTD
Alternative 19 = ADAEFFECTI
Alternative 20 = ES/STDSRES
Alternative 21 = KBSDVMAINT
Alternative 22 = DUMMY

B. The Attributes are:
Attribute 1 = INITIAL COST IMPCT
Attribute 2 = OPERATIONS COSTS
Attribute 3 = CREW PRODUCTIVITY
Attribute 4 = SAFETY
Attribute 5 = DEVELOPMENT RISK
Attribute 6 = RESOURCE REQTS IMP
Attribute 7 = GROWTH POTENTIAL
Attribute 8 = SPINOFF POTENTIAL

C. The Decision Makers are:
Individual 1 = INTRVW 01
Individual 2 = INTRVW 02
Individual 3 = INTRVW 03
Individual 4 = INTRVW 04
Individual 5 = INTRVW 05
Individual 6 = INTRVW 06
Individual 7 = INTRVW 07
Individual 8 = INTRVW 08
Individual 9 = INTRVW 09

D. Mode of Analysis Selected is: Detailed Analysis Mode

E. Run Option for Uncertainty is: Probabilistic

F. Type of Decision Model is: Detailed Non-Linear (Multiplicative) Model

SECTION II
INDIVIDUAL DECISION MAKER RANKINGS

This Section presents the results of a multi-attribute decision analysis for the Case HLEV000 with rankings for each decision maker.

Rankings for Decision Maker: INTRVW 01

Alternative	Value	Rank
FAULTPRED	0.9389	10
+/-	0.0103	
PROTOSCHED	0.9520	4
+/-	0.0080	
EXTFAULTTB	0.9434	7
+/-	0.0168	
KBSFAULTRE	0.9627	3
+/-	0.0075	
VDDTOMADMS	0.8666	20
+/-	0.0385	
ACCELSSMPM	0.8898	18
+/-	0.0186	
A&RPROTOTY	0.8719	19
+/-	0.0205	
DIAGES/EPS	0.9747	1
+/-	0.0054	
ABDUCT/EPS	0.9114	13
+/-	0.0171	
STD/TLS/ES	0.9628	2
+/-	0.0093	
AUTROBASSY	0.9422	9
+/-	0.0089	
TRTHERMPOS	0.9145	12
+/-	0.0101	
EVARETRIEV	0.9200	11
+/-	0.0178	
AUTROBSIM	0.9092	16
+/-	0.0117	
STEREOTELE	0.8983	17
+/-	0.0179	
WORLDMODEL	0.8460	21
+/-	0.0464	
ROBCTLASSY	0.9509	5
+/-	0.0073	
KNOWACQSTD	0.9098	15
+/-	0.0143	
ADAEFFECTI	0.9484	6
+/-	0.0115	
ES/STDSRES	0.9114	14
+/-	0.0214	
KBSDVMAINT	0.9430	8
+/-	0.0164	
DUMMY	0.4022	22
+/-	0.2463	

Rankings for Decision Maker: INTRVW 02

Alternative	Value	Rank
FAULTPRED	0.7858	8
+/-	0.0300	
PROTOSCHED	0.7442	12
+/-	0.0283	
EXTFAULTTB	0.7892	7
+/-	0.0291	
KBSFAULTRE	0.8452	2
+/-	0.0255	
VDDTOMADMS	0.6689	16
+/-	0.0362	
ACCELSSMPM	0.6327	21
+/-	0.0310	
A&RPROTOTY	0.6425	19
+/-	0.0275	
DIAGES/EPS	0.8165	4
+/-	0.0223	
ABDUCT/EPS	0.6875	14
+/-	0.0118	
STD/TLS/ES	0.8505	1
+/-	0.0254	
AUTROBASSY	0.7951	6
+/-	0.0307	
TRTHERMPOS	0.7064	13
+/-	0.0199	
EVARETRIEV	0.6811	15
+/-	0.0307	
AUTROBSIM	0.6592	17
+/-	0.0203	
STEREOTELE	0.6352	20
+/-	0.0439	
WORLDMODEL	0.6439	18
+/-	0.0348	
ROBCTLASSY	0.7841	9
+/-	0.0219	
KNOWACQSTD	0.7983	5
+/-	0.0288	
ADAEFFECTI	0.8190	3
+/-	0.0303	
ES/STDSRES	0.7595	11
+/-	0.0494	
KBSDVMAINT	0.7764	10
+/-	0.0345	
DUMMY	0.2413	22
+/-	0.1891	

Rankings for Decision Maker: INTRVW 03

Alternative	Value	Rank
FAULTPRED	0.7304	10
+/-	0.0195	
PROTOSCHED	0.7715	4
+/-	0.0163	
EXTFAULTTB	0.7604	6
+/-	0.0379	
KBSFAULTRE	0.7842	2
+/-	0.0161	
VDDTOMADMS	0.5941	21
+/-	0.0434	
ACCELSSMPM	0.6618	19
+/-	0.0232	
A&RPROTOTY	0.6928	13
+/-	0.0303	
DIAGES/EPS	0.8080	1
+/-	0.0134	
ABDUCT/EPS	0.6945	12
+/-	0.0192	
STD/TLS/ES	0.7791	3
+/-	0.0192	
AUTROBASSY	0.7378	9
+/-	0.0183	
TRTHERMPOS	0.6825	16
+/-	0.0156	
EVARETRIEV	0.7197	11
+/-	0.0238	
AUTROBSIM	0.6763	17
+/-	0.0149	
STEREOTELE	0.6871	15
+/-	0.0230	
WORLDMODEL	0.6003	20
+/-	0.0543	
ROBCTLASSY	0.7588	7
+/-	0.0160	
KNOWACQSTD	0.6698	18
+/-	0.0210	
ADAEFFECTI	0.7661	5
+/-	0.0212	
ES/STDSRES	0.6890	14
+/-	0.0342	
KBSDVMAINT	0.7428	8
+/-	0.0302	
DUMMY	0.2411	22
+/-	0.1647	

Rankings for Decision Maker: INTRVW 04

Alternative	Value	Rank
FAULTPRED	0.9389	10
+/-	0.0103	
PROTOSCHED	0.9520	6
+/-	0.0074	
EXTFAULTTB	0.9495	7
+/-	0.0107	
KBSFAULTRE	0.9582	3
+/-	0.0066	
VDDTOMADMS	0.8614	20
+/-	0.0305	
ACCELSSMPM	0.8990	18
+/-	0.0158	
A&RPROTOTY	0.9007	17
+/-	0.0174	
DIAGES/EPS	0.9727	1
+/-	0.0046	
ABDUCT/EPS	0.9012	16
+/-	0.0112	
STD/TLS/ES	0.9618	2
+/-	0.0078	
AUTROBASSY	0.9435	9
+/-	0.0076	
TRTHERMPOS	0.9210	11
+/-	0.0095	
EVARETRIEV	0.9208	12
+/-	0.0145	
AUTROBSIM	0.9023	15
+/-	0.0105	
STEREOTELE	0.8911	19
+/-	0.0152	
WORLDMODEL	0.8325	21
+/-	0.0359	
ROBCTLASSY	0.9552	4
+/-	0.0059	
KNOWACQSTD	0.9034	14
+/-	0.0141	
ADAEFFECTI	0.9490	8
+/-	0.0102	
ES/STDSRES	0.9106	13
+/-	0.0182	
KBSDVMAINT	0.9539	5
+/-	0.0094	
DUMMY	0.4109	22
+/-	0.2479	

Rankings for Decision Maker: INTRVW 05

Alternative	Value	Rank
FAULTPRED	0.9367	10
+/-	0.0078	
PROTOSCHED	0.9596	4
+/-	0.0050	
EXTFAULTTB	0.9503	7
+/-	0.0153	
KBSFAULTRE	0.9677	3
+/-	0.0058	
VDDTOMADMS	0.8649	20
+/-	0.0357	
ACCELSSMPM	0.9077	18
+/-	0.0133	
A&RPROTOTY	0.8923	19
+/-	0.0142	
DIAGES/EPS	0.9735	1
+/-	0.0046	
ABDUCT/EPS	0.9159	15
+/-	0.0168	
STD/TLS/ES	0.9694	2
+/-	0.0058	
AUTROBASSY	0.9428	9
+/-	0.0054	
TRTHERMPOS	0.9264	12
+/-	0.0076	
EVARETRIEV	0.9351	11
+/-	0.0128	
AUTROBSIM	0.9229	13
+/-	0.0082	
STEREOTELE	0.9081	17
+/-	0.0129	
WORLDMODEL	0.8607	21
+/-	0.0417	
ROBCTLASSY	0.9566	5
+/-	0.0046	
KNOWACQSTD	0.9167	14
+/-	0.0076	
ADAEFFECTI	0.9563	6
+/-	0.0066	
ES/STDSRES	0.9112	16
+/-	0.0150	
KBSDVMAINT	0.9447	8
+/-	0.0137	
DUMMY	0.4129	22
+/-	0.2542	

Rankings for Decision Maker: INTRVW 06

Alternative	Value	Rank
FAULTPRED	0.9308	10
+/-	0.0148	
PROTOSCHED	0.9473	4
+/-	0.0101	
EXTFAULTTB	0.9382	9
+/-	0.0201	
KBSFAULTRE	0.9565	3
+/-	0.0100	
VDDTOMADMS	0.8233	20
+/-	0.0465	
ACCELSSMPM	0.8768	18
+/-	0.0176	
A&RPROTOTY	0.8710	19
+/-	0.0203	
DIAGES/EPS	0.9696	1
+/-	0.0082	
ABDUCT/EPS	0.9060	13
+/-	0.0160	
STD/TLS/ES	0.9591	2
+/-	0.0109	
AUTROBASSY	0.9391	8
+/-	0.0141	
TRTHERMPOS	0.8882	15
+/-	0.0112	
EVARETRIEV	0.9077	11
+/-	0.0201	
AUTROBSIM	0.8872	16
+/-	0.0134	
STEREOTELE	0.8957	14
+/-	0.0238	
WORLDMODEL	0.8042	21
+/-	0.0574	
ROBCTLASSY	0.9449	5
+/-	0.0096	
KNOWACQSTD	0.8861	17
+/-	0.0235	
ADAEFFECTI	0.9424	6
+/-	0.0147	
ES/STDSRES	0.9075	12
+/-	0.0292	
KBSDVMAINT	0.9400	7
+/-	0.0187	
DUMMY	0.4134	22
+/-	0.2620	

Rankings for Decision Maker: INTRVW 07

Alternative	Value	Rank
FAULTPRED	0.7083	10
+/-	0.0198	
PROTOSCHED	0.7227	9
+/-	0.0180	
EXTFAULTTB	0.7445	6
+/-	0.0388	
KBSFAULTRE	0.7496	5
+/-	0.0213	
VDDTOMADMS	0.5594	20
+/-	0.0527	
ACCELSSMPM	0.6609	14
+/-	0.0202	
A&RPROTOTY	0.5708	19
+/-	0.0265	
DIAGES/EPS	0.7902	1
+/-	0.0216	
ABDUCT/EPS	0.6459	16
+/-	0.0327	
STD/TLS/ES	0.7832	2
+/-	0.0229	
AUTROBASSY	0.7435	7
+/-	0.0175	
TRTHERMPOS	0.6827	11
+/-	0.0140	
EVARETRIEV	0.6745	12
+/-	0.0273	
AUTROBSIM	0.6557	15
+/-	0.0191	
STEREOTELE	0.6363	17
+/-	0.0262	
WORLDMODEL	0.5357	21
+/-	0.0560	
ROBCTLASSY	0.7511	3
+/-	0.0157	
KNOWACQSTD	0.6268	18
+/-	0.0187	
ADAEFFECTI	0.7339	8
+/-	0.0215	
ES/STDSRES	0.6640	13
+/-	0.0292	
KBSDVMAINT	0.7496	4
+/-	0.0364	
DUMMY	0.2112	22
+/-	0.1519	

Rankings for Decision Maker: INTRVW 08

Alternative	Value	Rank
FAULTPRED	0.9143	10
+/-	0.0109	
PROTOSCHED	0.9263	7
+/-	0.0095	
EXTFAULTTB	0.9303	6
+/-	0.0162	
KBSFAULTRE	0.9450	3
+/-	0.0077	
VDDTOMADMS	0.8150	19
+/-	0.0357	
ACCELSSMPM	0.8665	18
+/-	0.0173	
A&RPROTOTY	0.8126	20
+/-	0.0244	
DIAGES/EPS	0.9534	1
+/-	0.0059	
ABDUCT/EPS	0.8740	16
+/-	0.0136	
STD/TLS/ES	0.9491	2
+/-	0.0086	
AUTROBASSY	0.9261	8
+/-	0.0087	
TRTHERMPOS	0.8947	11
+/-	0.0099	
EVARETRIEV	0.8932	12
+/-	0.0160	
AUTROBSIM	0.8688	17
+/-	0.0114	
STEREOTELE	0.8795	15
+/-	0.0151	
WORLDMODEL	0.7992	21
+/-	0.0441	
ROBCTLASSY	0.9321	5
+/-	0.0075	
KNOWACQSTD	0.8849	14
+/-	0.0138	
ADAEFFECTI	0.9348	4
+/-	0.0112	
ES/STDSRES	0.8854	13
+/-	0.0211	
KBSDVMAINT	0.9259	9
+/-	0.0149	
DUMMY	0.3772	22
+/-	0.2333	

Rankings for Decision Maker: INTRVW 09

Alternative	Value	Rank
FAULTPRED	0.9298	10
+/-	0.0132	
PROTOSCHED	0.9491	5
+/-	0.0088	
EXTFAULTTB	0.9434	6
+/-	0.0184	
KBSFAULTRE	0.9642	3
+/-	0.0077	
VDDTOMADMS	0.8196	20
+/-	0.0441	
ACCELSSMPM	0.8840	18
+/-	0.0169	
A&RPROTOTY	0.8575	19
+/-	0.0251	
DIAGES/EPS	0.9718	1
+/-	0.0056	
ABDUCT/EPS	0.9007	16
+/-	0.0144	
STD/TLS/ES	0.9654	2
+/-	0.0077	
AUTROBASSY	0.9347	9
+/-	0.0113	
TRTHERMPOS	0.9036	13
+/-	0.0116	
EVARETRIEV	0.9196	11
+/-	0.0160	
AUTROBSIM	0.8861	17
+/-	0.0121	
STEREOTELE	0.9128	12
+/-	0.0165	
WORLDMODEL	0.8176	21
+/-	0.0554	
ROBCTLASSY	0.9413	7
+/-	0.0086	
KNOWACQSTD	0.9034	14
+/-	0.0163	
ADAEFFECTI	0.9525	4
+/-	0.0110	
ES/STDSRES	0.9022	15
+/-	0.0229	
KBSDVMAINT	0.9362	8
+/-	0.0167	
DUMMY	0.4199	22
+/-	0.2622	

The rankings are in Agreement at a 95 percent significance level.
The value of the concordance (0=agreement, 1=disagreement) is 0.93

SECTION III
DECISION MAKER GROUP RANKINGS

This Section presents the results for Case HLEV000 with rankings for all decision makers as a group using three different rules.

Additive Rule = Sum of Scores
Nash Bargaining Rule = Product of Scores
Rank Sum Rule = Sum of Ranks

	Additive Rule		Nash Bargaining Rule		Rank Sum Rule	
Alternative	Value	Rank	Value	Rank	Value	Rank
FAULTPRED	0.8682	10	0.8631	10	0.5820	10
PROTOSCHED	0.8805	7	0.8750	7	0.7566	6
EXTFAULTTB	0.8832	6	0.8790	6	0.7249	7
KBSFAULTRE	0.9037	3	0.8998	3	0.9048	3
VDDTOMADMS	0.7637	20	0.7542	20	0.1164	20
ACCELSSMPM	0.8088	18	0.8005	18	0.1905	18
A&RPROTOTY	0.7902	19	0.7809	19	0.1799	19
DIAGES/EPS	0.9145	1	0.9110	1	0.9841	1
ABDUCT/EPS	0.8264	15	0.8188	15	0.3545	15
STD/TLS/ES	0.9089	2	0.9055	2	0.9524	2
AUTROBASSY	0.8783	9	0.8739	9	0.6561	9
TRTHERMPOS	0.8356	13	0.8288	13	0.4444	12
EVARETRIEV	0.8413	11	0.8340	11	0.4868	11
AUTROBSIM	0.8186	16	0.8107	16	0.2910	16
STEREOTELE	0.8160	17	0.8070	17	0.2751	17
WORLDMODEL	0.7489	21	0.7393	21	0.0688	21
ROBCTLASSY	0.8861	5	0.8817	5	0.7831	4
KNOWACQSTD	0.8333	14	0.8260	14	0.3651	14
ADAEFFECTI	0.8892	4	0.8849	4	0.7831	4
ES/STDSRES	0.8379	12	0.8317	12	0.4074	13
KBSDVMAINT	0.8792	8	0.8746	8	0.6931	8
DUMMY	0.3478	22	0.3362	22	0.0000	22

The group rankings are in Agreement at a 95 percent significance level.
The value of the concordance (0=agreement, 1=disagreement) is 1.00

SECTION IV
DATA INPUTS

This Section presents the inputs for Case HLEV000 used to compute the rankings.

A. The Attribute State/Distribution Inputs

Attribute States for ALTERNATIVE: FAULTPRED

Point Value for INITIAL COST IMPCT = 6.0000

Cumulative Distribution for OPERATIONS COSTS

State	CDF	State	CDF	State	CDF
3.0000	0.00	4.0000	0.50	6.0000	1.00
3.7000	0.25	4.8000	0.75		

Point Value for CREW PRODUCTIVITY = 5.0000

Cumulative Distribution for SAFETY

State	CDF	State	CDF	State	CDF
3.0000	0.00	6.0000	0.50	8.0000	1.00
4.8000	0.25	6.8000	0.75		

Point Value for DEVELOPMENT RISK = 5.0000

Cumulative Distribution for RESOURCE REQTS IMP

State	CDF	State	CDF	State	CDF
5.0000	0.00	6.0000	0.50	8.0000	1.00
5.9000	0.25	7.2000	0.75		

Cumulative Distribution for GROWTH POTENTIAL

State	CDF	State	CDF	State	CDF
6.0000	0.00	7.0000	0.50	8.0000	1.00
6.5000	0.25	7.5000	0.75		

Cumulative Distribution for SPINOFF POTENTIAL

State	CDF	State	CDF	State	CDF
0.0000	0.00	1.5000	0.50	3.0000	1.00
0.7500	0.25	2.2500	0.75		

Attribute States for ALTERNATIVE: PROTOSCHED

Point Value for INITIAL COST IMPCT = 5.0000

Cumulative Distribution for OPERATIONS COSTS

State	CDF	State	CDF	State	CDF
5.0000	0.00	6.5000	0.50	7.0000	1.00
5.4000	0.25	6.5000	0.75		

Cumulative Distribution for CREW PRODUCTIVITY

State	CDF	State	CDF	State	CDF
7.0000	0.00	7.5000	0.50	8.0000	1.00
7.2500	0.25	7.7500	0.75		

Cumulative Distribution for SAFETY

State	CDF	State	CDF	State	CDF
1.0000	0.00	3.0000	0.50	7.0000	1.00
2.1000	0.25	4.2000	0.75		

Point Value for DEVELOPMENT RISK = 5.0000

Cumulative Distribution for RESOURCE REQTS IMP

State	CDF	State	CDF	State	CDF
3.0000	0.00	4.0000	0.50	5.0000	1.00
3.5000	0.25	4.5000	0.75		

Cumulative Distribution for GROWTH POTENTIAL

State	CDF	State	CDF	State	CDF
6.0000	0.00	7.0000	0.50	8.0000	1.00
6.5000	0.25	7.5000	0.75		

Cumulative Distribution for SPINOFF POTENTIAL

State	CDF	State	CDF	State	CDF
6.0000	0.00	7.5000	0.50	9.0000	1.00
6.7500	0.25	8.2500	0.75		

Attribute States for ALTERNATIVE: EXTFAULTTB

Point Value for INITIAL COST IMPCT = 7.0000

Cumulative Distribution for OPERATIONS COSTS

State	CDF	State	CDF	State	CDF
3.5000	0.00	4.0000	0.50	5.5000	1.00
3.9000	0.25	4.9000	0.75		

Cumulative Distribution for CREW PRODUCTIVITY

State	CDF	State	CDF	State	CDF
4.0000	0.00	4.5000	0.50	5.0000	1.00
4.2500	0.25	4.7500	0.75		

Cumulative Distribution for SAFETY

State	CDF	State	CDF	State	CDF
2.0000	0.00	5.0000	0.50	8.0000	1.00
3.8000	0.25	6.3000	0.75		

Point Value for DEVELOPMENT RISK = 8.0000

Cumulative Distribution for RESOURCE REQTS IMP

State	CDF	State	CDF	State	CDF
5.0000	0.00	6.0000	0.50	6.8000	1.00
5.8000	0.25	6.6000	0.75		

Cumulative Distribution for GROWTH POTENTIAL

State	CDF	State	CDF	State	CDF
0.0000	0.00	5.0000	0.50	10.0000	1.00
2.5000	0.25	7.5000	0.75		

Cumulative Distribution for SPINOFF POTENTIAL

State	CDF	State	CDF	State	CDF
0.0000	0.00	5.0000	0.50	10.0000	1.00
2.5000	0.25	7.5000	0.75		

Attribute States for ALTERNATIVE: KBSFAULTRE

Cumulative Distribution for INITIAL COST IMPCT

State	CDF	State	CDF	State	CDF
8.0000	0.00	8.5000	0.50	9.0000	1.00
8.2500	0.25	8.7500	0.75		

Cumulative Distribution for OPERATIONS COSTS

State	CDF	State	CDF	State	CDF
5.0000	0.00	6.5000	0.50	8.0000	1.00
6.4000	0.25	7.2000	0.75		

Point Value for CREW PRODUCTIVITY = 6.0000

Cumulative Distribution for SAFETY

State	CDF	State	CDF	State	CDF
2.0000	0.00	5.0000	0.50	8.0000	1.00
3.8000	0.25	6.4000	0.75		

Point Value for DEVELOPMENT RISK = 4.0000

Cumulative Distribution for RESOURCE REQTS IMP

State	CDF	State	CDF	State	CDF
4.0000	0.00	4.5000	0.50	5.0000	1.00
4.2500	0.25	4.7500	0.75		

Cumulative Distribution for GROWTH POTENTIAL

State	CDF	State	CDF	State	CDF
5.0000	0.00	7.0000	0.50	9.0000	1.00
6.0000	0.25	8.0000	0.75		

Cumulative Distribution for SPINOFF POTENTIAL

State	CDF	State	CDF	State	CDF
5.0000	0.00	6.0000	0.50	7.0000	1.00
5.5000	0.25	6.5000	0.75		

Attribute States for ALTERNATIVE: VDDTOMADMS

Point Value for INITIAL COST IMPCT = 5.0000

Cumulative Distribution for OPERATIONS COSTS

State	CDF	State	CDF	State	CDF
3.0000	0.00	5.0000	0.50	6.5000	1.00
4.5000	0.25	5.4000	0.75		

Cumulative Distribution for CREW PRODUCTIVITY

State	CDF	State	CDF	State	CDF
4.0000	0.00	4.5000	0.50	5.0000	1.00
4.2500	0.25	4.7500	0.75		

Cumulative Distribution for SAFETY

State	CDF	State	CDF	State	CDF
1.0000	0.00	3.0000	0.50	6.0000	1.00
2.0000	0.25	4.3000	0.75		

Point Value for DEVELOPMENT RISK = 2.0000

Cumulative Distribution for RESOURCE REQTS IMP

State	CDF	State	CDF	State	CDF
1.0000	0.00	2.5000	0.50	3.0000	1.00
2.3100	0.25	2.7500	0.75		

Cumulative Distribution for GROWTH POTENTIAL

State	CDF	State	CDF	State	CDF
0.0000	0.00	5.0000	0.50	10.0000	1.00
2.5000	0.25	7.5000	0.75		

Cumulative Distribution for SPINOFF POTENTIAL

State	CDF	State	CDF	State	CDF
0.0000	0.00	1.5000	0.50	3.0000	1.00
0.7500	0.25	2.2500	0.75		

Attribute States for ALTERNATIVE: ACCELSSMPM

Point Value for INITIAL COST IMPCT = 4.0000

Cumulative Distribution for OPERATIONS COSTS

State	CDF	State	CDF	State	CDF
2.0000	0.00	3.5000	0.50	5.0000	1.00
2.2000	0.25	4.0000	0.75		

Point Value for CREW PRODUCTIVITY = 3.0000

Cumulative Distribution for SAFETY

State	CDF	State	CDF	State	CDF
1.0000	0.00	2.0000	0.50	5.0000	1.00
1.6000	0.25	3.3000	0.75		

Point Value for DEVELOPMENT RISK = 8.0000

Cumulative Distribution for RESOURCE REQTS IMP

State	CDF	State	CDF	State	CDF
4.0000	0.00	5.0000	0.50	5.5000	1.00
4.5000	0.25	5.4300	0.75		

Cumulative Distribution for GROWTH POTENTIAL

State	CDF	State	CDF	State	CDF
6.0000	0.00	7.0000	0.50	8.0000	1.00
6.5000	0.25	7.5000	0.75		

Cumulative Distribution for SPINOFF POTENTIAL

State	CDF	State	CDF	State	CDF
0.0000	0.00	1.6660	0.50	5.0000	1.00
0.0000	0.25	3.3330	0.75		

Attribute States for ALTERNATIVE: A&RPROTOTY

Point Value for INITIAL COST IMPCT = 2.0000

Cumulative Distribution for OPERATIONS COSTS

State	CDF	State	CDF	State	CDF
3.0000	0.00	3.5000	0.50	5.0000	1.00
3.4000	0.25	4.8000	0.75		

Cumulative Distribution for CREW PRODUCTIVITY

State	CDF	State	CDF	State	CDF
9.0000	0.00	9.5000	0.50	10.0000	1.00
9.2500	0.25	9.7500	0.75		

Cumulative Distribution for SAFETY

State	CDF	State	CDF	State	CDF
0.0000	0.00	2.0000	0.50	4.0000	1.00
1.2000	0.25	2.8000	0.75		

Point Value for DEVELOPMENT RISK = 1.0000

Cumulative Distribution for RESOURCE REQTS IMP

State	CDF	State	CDF	State	CDF
4.0000	0.00	5.0000	0.50	8.0000	1.00
4.2000	0.25	5.3000	0.75		

Cumulative Distribution for GROWTH POTENTIAL

State	CDF	State	CDF	State	CDF
0.0000	0.00	2.5000	0.50	5.0000	1.00
1.2500	0.25	3.7500	0.75		

Cumulative Distribution for SPINOFF POTENTIAL

State	CDF	State	CDF	State	CDF
0.0000	0.00	1.3330	0.50	4.0000	1.00
0.0000	0.25	2.6670	0.75		

Attribute States for ALTERNATIVE: DIAGES/EPS

Point Value for INITIAL COST IMPCT = 6.0000

Cumulative Distribution for OPERATIONS COSTS

State	CDF	State	CDF	State	CDF
7.0000	0.00	8.7000	0.50	9.0000	1.00
7.2000	0.25	8.7000	0.75		

Cumulative Distribution for CREW PRODUCTIVITY

State	CDF	State	CDF	State	CDF
5.0000	0.00	5.5000	0.50	6.0000	1.00
5.2500	0.25	5.7500	0.75		

Cumulative Distribution for SAFETY

State	CDF	State	CDF	State	CDF
3.0000	0.00	5.0000	0.50	8.0000	1.00
4.2000	0.25	6.1000	0.75		

Point Value for DEVELOPMENT RISK = 6.0000

Cumulative Distribution for RESOURCE REQTS IMP

State	CDF	State	CDF	State	CDF
5.0000	0.00	6.0000	0.50	6.5000	1.00
5.7000	0.25	6.2500	0.75		

Cumulative Distribution for GROWTH POTENTIAL

State	CDF	State	CDF	State	CDF
7.0000	0.00	8.5000	0.50	10.0000	1.00
7.7500	0.25	9.2500	0.75		

Cumulative Distribution for SPINOFF POTENTIAL

State	CDF	State	CDF	State	CDF
5.0000	0.00	6.0000	0.50	7.0000	1.00
5.5000	0.25	6.5000	0.75		

Attribute States for ALTERNATIVE: ABDUCT/EPS

Point Value for INITIAL COST IMPCT = 4.0000

Cumulative Distribution for OPERATIONS COSTS

State	CDF	State	CDF	State	CDF
2.0000	0.00	3.0000	0.50	4.0000	1.00
2.5000	0.25	3.5000	0.75		

Point Value for CREW PRODUCTIVITY = 5.0000

Point Value for SAFETY = 5.0000

Point Value for DEVELOPMENT RISK = 3.0000

Cumulative Distribution for RESOURCE REQTS IMP

State	CDF	State	CDF	State	CDF
3.0000	0.00	3.5000	0.50	4.0000	1.00
3.2500	0.25	3.7500	0.75		

Cumulative Distribution for GROWTH POTENTIAL

State	CDF	State	CDF	State	CDF
5.0000	0.00	7.5000	0.50	10.0000	1.00
6.2500	0.25	8.7500	0.75		

Cumulative Distribution for SPINOFF POTENTIAL

State	CDF	State	CDF	State	CDF
4.0000	0.00	6.0000	0.50	8.0000	1.00
5.0000	0.25	7.0000	0.75		

Attribute States for ALTERNATIVE: STD/TLS/ES

Point Value for INITIAL COST IMPCT = 9.0000

Cumulative Distribution for OPERATIONS COSTS

State	CDF	State	CDF	State	CDF
3.0000	0.00	5.0000	0.50	8.0000	1.00
4.8000	0.25	5.3000	0.75		

Cumulative Distribution for CREW PRODUCTIVITY

State	CDF	State	CDF	State	CDF
5.0000	0.00	5.5000	0.50	6.0000	1.00
5.2500	0.25	5.7500	0.75		

Cumulative Distribution for SAFETY

State	CDF	State	CDF	State	CDF
2.0000	0.00	6.0000	0.50	8.0000	1.00
4.5000	0.25	6.7000	0.75		

Point Value for DEVELOPMENT RISK = 8.0000

Cumulative Distribution for RESOURCE REQTS IMP

State	CDF	State	CDF	State	CDF
4.0000	0.00	5.0000	0.50	6.0000	1.00
4.5000	0.25	5.5000	0.75		

Cumulative Distribution for GROWTH POTENTIAL

State	CDF	State	CDF	State	CDF
5.0000	0.00	7.0000	0.50	9.0000	1.00
6.0000	0.25	8.0000	0.75		

Cumulative Distribution for SPINOFF POTENTIAL

State	CDF	State	CDF	State	CDF
0.0000	0.00	1.5000	0.50	3.0000	1.00
0.7500	0.25	2.2500	0.75		

Attribute States for ALTERNATIVE: AUTROBASSY

Point Value for INITIAL COST IMPCT = 7.0000

Cumulative Distribution for OPERATIONS COSTS

State	CDF	State	CDF	State	CDF
3.0000	0.00	3.7000	0.50	4.0000	1.00
3.6000	0.25	3.7000	0.75		

Point Value for CREW PRODUCTIVITY = 4.0000

Cumulative Distribution for SAFETY

State	CDF	State	CDF	State	CDF
2.0000	0.00	7.0000	0.50	8.0000	1.00
5.7000	0.25	7.4000	0.75		

Point Value for DEVELOPMENT RISK = 9.0000

Cumulative Distribution for RESOURCE REQTS IMP

State	CDF	State	CDF	State	CDF
4.0000	0.00	4.5000	0.50	5.0000	1.00
4.2500	0.25	4.7500	0.75		

Cumulative Distribution for GROWTH POTENTIAL

State	CDF	State	CDF	State	CDF
6.0000	0.00	6.0000	0.50	8.0000	1.00
6.0000	0.25	7.0000	0.75		

Cumulative Distribution for SPINOFF POTENTIAL

State	CDF	State	CDF	State	CDF
0.0000	0.00	0.0000	0.50	4.0000	1.00
0.0000	0.25	2.0000	0.75		

Attribute States for ALTERNATIVE: TRTHERMPOS

Cumulative Distribution for INITIAL COST IMPCT

State	CDF	State	CDF	State	CDF
5.0000	0.00	6.0000	0.50	7.0000	1.00
5.5000	0.25	6.5000	0.75		

Cumulative Distribution for OPERATIONS COSTS

State	CDF	State	CDF	State	CDF
5.0000	0.00	6.0000	0.50	7.0000	1.00
5.5000	0.25	6.5000	0.75		

Point Value for CREW PRODUCTIVITY = 3.0000

Cumulative Distribution for SAFETY

State	CDF	State	CDF	State	CDF
1.0000	0.00	2.0000	0.50	3.0000	1.00
1.6000	0.25	2.4000	0.75		

Point Value for DEVELOPMENT RISK = 8.0000

Cumulative Distribution for RESOURCE REQTS IMP

State	CDF	State	CDF	State	CDF
4.0000	0.00	4.5000	0.50	5.0000	1.00
4.2500	0.25	4.7500	0.75		

Cumulative Distribution for GROWTH POTENTIAL

State	CDF	State	CDF	State	CDF
5.0000	0.00	6.0000	0.50	7.0000	1.00
5.5000	0.25	6.5000	0.75		

Cumulative Distribution for SPINOFF POTENTIAL

State	CDF	State	CDF	State	CDF
0.0000	0.00	1.0000	0.50	3.0000	1.00
0.0000	0.25	2.0000	0.75		

Attribute States for ALTERNATIVE: EVARETRIEV

Point Value for INITIAL COST IMPCT = 4.0000

Cumulative Distribution for OPERATIONS COSTS

State	CDF	State	CDF	State	CDF
3.0000	0.00	5.0000	0.50	6.0000	1.00
4.5000	0.25	5.4000	0.75		

Cumulative Distribution for CREW PRODUCTIVITY

State	CDF	State	CDF	State	CDF
4.0000	0.00	4.5000	0.50	5.0000	1.00
4.2500	0.25	4.7500	0.75		

Cumulative Distribution for SAFETY

State	CDF	State	CDF	State	CDF
1.0000	0.00	2.0000	0.50	6.0000	1.00
1.3000	0.25	3.5000	0.75		

Point Value for DEVELOPMENT RISK = 5.0000

Cumulative Distribution for RESOURCE REQTS IMP

State	CDF	State	CDF	State	CDF
4.0000	0.00	5.5000	0.50	7.0000	1.00
5.4000	0.25	5.7000	0.75		

Cumulative Distribution for GROWTH POTENTIAL

State	CDF	State	CDF	State	CDF
5.0000	0.00	7.0000	0.50	9.0000	1.00
6.0000	0.25	8.0000	0.75		

Cumulative Distribution for SPINOFF POTENTIAL

State	CDF	State	CDF	State	CDF
5.0000	0.00	7.0000	0.50	9.0000	1.00
6.0000	0.25	8.0000	0.75		

Attribute States for ALTERNATIVE: AUTROBSIM

Cumulative Distribution for INITIAL COST IMPCT

State	CDF	State	CDF	State	CDF
4.0000	0.00	4.5000	0.50	5.0000	1.00
4.2500	0.25	4.7500	0.75		

Cumulative Distribution for OPERATIONS COSTS

State	CDF	State	CDF	State	CDF
3.0000	0.00	4.0000	0.50	4.8000	1.00
3.9000	0.25	4.4000	0.75		

Point Value for CREW PRODUCTIVITY = 5.0000

Cumulative Distribution for SAFETY

State	CDF	State	CDF	State	CDF
0.0000	0.00	2.0000	0.50	4.0000	1.00
1.2000	0.25	2.7000	0.75		

Point Value for DEVELOPMENT RISK = 4.0000

Cumulative Distribution for RESOURCE REQTS IMP

State	CDF	State	CDF	State	CDF
3.5000	0.00	4.0000	0.50	4.5000	1.00
3.8000	0.25	4.3000	0.75		

Cumulative Distribution for GROWTH POTENTIAL

State	CDF	State	CDF	State	CDF
7.0000	0.00	8.0000	0.50	9.0000	1.00
7.5000	0.25	8.5000	0.75		

Cumulative Distribution for SPINOFF POTENTIAL

State	CDF	State	CDF	State	CDF
3.0000	0.00	4.0000	0.50	5.0000	1.00
3.5000	0.25	4.5000	0.75		

Attribute States for ALTERNATIVE: STEREOTELE

Point Value for INITIAL COST IMPCT = 3.0000

Cumulative Distribution for OPERATIONS COSTS

State	CDF	State	CDF	State	CDF
4.0000	0.00	5.0000	0.50	7.0000	1.00
4.8000	0.25	5.4000	0.75		

Point Value for CREW PRODUCTIVITY = 0.0000

Cumulative Distribution for SAFETY

State	CDF	State	CDF	State	CDF
2.0000	0.00	5.0000	0.50	8.0000	1.00
3.8000	0.25	6.3000	0.75		

Point Value for DEVELOPMENT RISK = 5.0000

Cumulative Distribution for RESOURCE REQTS IMP

State	CDF	State	CDF	State	CDF
4.5000	0.00	5.0000	0.50	6.0000	1.00
4.9000	0.25	5.6000	0.75		

Cumulative Distribution for GROWTH POTENTIAL

State	CDF	State	CDF	State	CDF
6.0000	0.00	7.5000	0.50	9.0000	1.00
6.7500	0.25	8.2500	0.75		

Cumulative Distribution for SPINOFF POTENTIAL

State	CDF	State	CDF	State	CDF
5.0000	0.00	7.0000	0.50	9.0000	1.00
6.0000	0.25	8.0000	0.75		

Attribute States for ALTERNATIVE: WORLDMODEL

Point Value for INITIAL COST IMPCT = 6.0000

Cumulative Distribution for OPERATIONS COSTS

State	CDF	State	CDF	State	CDF
2.0000	0.00	3.0000	0.50	4.5000	1.00
2.8000	0.25	4.2000	0.75		

Point Value for CREW PRODUCTIVITY = 5.0000

Cumulative Distribution for SAFETY

State	CDF	State	CDF	State	CDF
0.0000	0.00	2.0000	0.50	5.0000	1.00
1.2000	0.25	2.7000	0.75		

Point Value for DEVELOPMENT RISK = 0.0000

Cumulative Distribution for RESOURCE REQTS IMP

State	CDF	State	CDF	State	CDF
0.5000	0.00	2.0000	0.50	3.0000	1.00
1.8000	0.25	2.1000	0.75		

Cumulative Distribution for GROWTH POTENTIAL

State	CDF	State	CDF	State	CDF
0.0000	0.00	5.0000	0.50	10.0000	1.00
2.5000	0.25	7.5000	0.75		

Cumulative Distribution for SPINOFF POTENTIAL

State	CDF	State	CDF	State	CDF
0.0000	0.00	5.0000	0.50	10.0000	1.00
2.5000	0.25	7.5000	0.75		

Attribute States for ALTERNATIVE: ROBCTLASSY

Point Value for INITIAL COST IMPCT = 7.0000

Cumulative Distribution for OPERATIONS COSTS

State	CDF	State	CDF	State	CDF
3.5000	0.00	4.0000	0.50	5.0000	1.00
3.9000	0.25	4.4000	0.75		

Point Value for CREW PRODUCTIVITY = 7.0000

Cumulative Distribution for SAFETY

State	CDF	State	CDF	State	CDF
2.0000	0.00	4.0000	0.50	7.0000	1.00
3.1000	0.25	4.9000	0.75		

Point Value for DEVELOPMENT RISK = 8.0000

Cumulative Distribution for RESOURCE REQTS IMP

State	CDF	State	CDF	State	CDF
4.5000	0.00	5.0000	0.50	6.0000	1.00
4.9000	0.25	5.1000	0.75		

Cumulative Distribution for GROWTH POTENTIAL

State	CDF	State	CDF	State	CDF
6.0000	0.00	6.0000	0.50	8.0000	1.00
6.0000	0.25	7.0000	0.75		

Cumulative Distribution for SPINOFF POTENTIAL

State	CDF	State	CDF	State	CDF
0.0000	0.00	1.3330	0.50	4.0000	1.00
0.0000	0.25	2.6700	0.75		

Attribute States for ALTERNATIVE: KNOWACQSTD

Point Value for INITIAL COST IMPCT = 8.0000

Cumulative Distribution for OPERATIONS COSTS

State	CDF	State	CDF	State	CDF
3.0000	0.00	4.0000	0.50	5.0000	1.00
3.2000	0.25	4.5000	0.75		

Point Value for CREW PRODUCTIVITY = 5.0000

Cumulative Distribution for SAFETY

State	CDF	State	CDF	State	CDF
2.0000	0.00	6.0000	0.50	8.0000	1.00
4.5000	0.25	6.7000	0.75		

Point Value for DEVELOPMENT RISK = 0.0000

Cumulative Distribution for RESOURCE REQTS IMP

State	CDF	State	CDF	State	CDF
4.0000	0.00	5.0000	0.50	6.0000	1.00
4.5000	0.25	5.5000	0.75		

Cumulative Distribution for GROWTH POTENTIAL

State	CDF	State	CDF	State	CDF
5.0000	0.00	6.0000	0.50	7.0000	1.00
5.5000	0.25	6.5000	0.75		

Cumulative Distribution for SPINOFF POTENTIAL

State	CDF	State	CDF	State	CDF
0.0000	0.00	1.5000	0.50	3.0000	1.00
0.7500	0.25	2.2500	0.75		

Attribute States for ALTERNATIVE: ADAEFFECTI

Point Value for INITIAL COST IMPCT = 8.0000

Cumulative Distribution for OPERATIONS COSTS

State	CDF	State	CDF	State	CDF
4.0000	0.00	5.0000	0.50	7.0000	1.00
4.7000	0.25	6.5000	0.75		

Point Value for CREW PRODUCTIVITY = 5.0000

Cumulative Distribution for SAFETY

State	CDF	State	CDF	State	CDF
2.0000	0.00	5.0000	0.50	8.0000	1.00
3.8000	0.25	6.3000	0.75		

Cumulative Distribution for DEVELOPMENT RISK

State	CDF	State	CDF	State	CDF
5.0000	0.00	6.0000	0.50	7.0000	1.00
5.5000	0.25	6.5000	0.75		

Cumulative Distribution for RESOURCE REQTS IMP

State	CDF	State	CDF	State	CDF
4.0000	0.00	5.0000	0.50	6.0000	1.00
4.5000	0.25	5.5000	0.75		

Cumulative Distribution for GROWTH POTENTIAL

State	CDF	State	CDF	State	CDF
3.0000	0.00	5.0000	0.50	7.0000	1.00
4.0000	0.25	6.0000	0.75		

Cumulative Distribution for SPINOFF POTENTIAL

State	CDF	State	CDF	State	CDF
5.0000	0.00	6.0000	0.50	7.0000	1.00
5.5000	0.25	6.5000	0.75		

Attribute States for ALTERNATIVE: ES/STDSRES

Cumulative Distribution for INITIAL COST IMPCT

State	CDF	State	CDF	State	CDF
6.0000	0.00	6.5000	0.50	7.0000	1.00
6.2500	0.25	6.7500	0.75		

Cumulative Distribution for OPERATIONS COSTS

State	CDF	State	CDF	State	CDF
1.0000	0.00	3.0000	0.50	5.0000	1.00
1.5000	0.25	3.2000	0.75		

Point Value for CREW PRODUCTIVITY = 5.0000

Cumulative Distribution for SAFETY

State	CDF	State	CDF	State	CDF
1.0000	0.00	6.0000	0.50	9.0000	1.00
3.8000	0.25	7.1000	0.75		

Point Value for DEVELOPMENT RISK = 4.0000

Cumulative Distribution for RESOURCE REQTS IMP

State	CDF	State	CDF	State	CDF
4.0000	0.00	5.0000	0.50	6.0000	1.00
4.5000	0.25	5.5000	0.75		

Cumulative Distribution for GROWTH POTENTIAL

State	CDF	State	CDF	State	CDF
5.0000	0.00	6.5000	0.50	8.0000	1.00
5.7500	0.25	7.2500	0.75		

Cumulative Distribution for SPINOFF POTENTIAL

State	CDF	State	CDF	State	CDF
0.0000	0.00	1.5000	0.50	3.0000	1.00
0.7500	0.25	2.2500	0.75		

Attribute States for ALTERNATIVE: KBSDVMAINT

Point Value for INITIAL COST IMPCT = 6.0000

Cumulative Distribution for OPERATIONS COSTS

State	CDF	State	CDF	State	CDF
3.0000	0.00	4.0000	0.50	5.0000	1.00
3.7000	0.25	4.5000	0.75		

Point Value for CREW PRODUCTIVITY = 5.0000

Cumulative Distribution for SAFETY

State	CDF	State	CDF	State	CDF
2.0000	0.00	6.0000	0.50	8.0000	1.00
4.5000	0.25	6.8000	0.75		

Point Value for DEVELOPMENT RISK = 10.0000

Cumulative Distribution for RESOURCE REQTS IMP

State	CDF	State	CDF	State	CDF
4.0000	0.00	5.0000	0.50	6.0000	1.00
4.5000	0.25	5.5000	0.75		

Cumulative Distribution for GROWTH POTENTIAL

State	CDF	State	CDF	State	CDF
0.0000	0.00	5.0000	0.50	10.0000	1.00
2.5000	0.25	7.5000	0.75		

Cumulative Distribution for SPINOFF POTENTIAL

State	CDF	State	CDF	State	CDF
0.0000	0.00	1.5000	0.50	3.0000	1.00
0.7500	0.25	2.2500	0.75		

Attribute States for ALTERNATIVE: DUMMY

Cumulative Distribution for INITIAL COST IMPCT

State	CDF	State	CDF	State	CDF
0.0000	0.00	0.0000	0.50	10.0000	1.00
0.0000	0.25	0.0000	0.75		

Cumulative Distribution for OPERATIONS COSTS

State	CDF	State	CDF	State	CDF
0.0000	0.00	0.0000	0.50	10.0000	1.00
0.0000	0.25	0.0000	0.75		

Cumulative Distribution for CREW PRODUCTIVITY

State	CDF	State	CDF	State	CDF
0.0000	0.00	0.0000	0.50	10.0000	1.00
0.0000	0.25	0.0000	0.75		

Cumulative Distribution for SAFETY

State	CDF	State	CDF	State	CDF
0.0000	0.00	0.0000	0.50	10.0000	1.00
0.0000	0.25	0.0000	0.75		

Cumulative Distribution for DEVELOPMENT RISK

State	CDF	State	CDF	State	CDF
0.0000	0.00	0.0000	0.50	10.0000	1.00
0.0000	0.25	0.0000	0.75		

Cumulative Distribution for RESOURCE REQTS IMP

State	CDF	State	CDF	State	CDF
0.0000	0.00	0.0000	0.50	10.0000	1.00
0.0000	0.25	0.0000	0.75		

Cumulative Distribution for GROWTH POTENTIAL

State	CDF	State	CDF	State	CDF
0.0000	0.00	0.0000	0.50	10.0000	1.00
0.0000	0.25	0.0000	0.75		

Cumulative Distribution for SPINOFF POTENTIAL

State	CDF	State	CDF	State	CDF
0.0000	0.00	0.0000	0.50	10.0000	1.00
0.0000	0.25	0.0000	0.75		

B. The Preference Inputs for Each Decision Maker

Attribute Preferences for Individual: INTRVW 01

Scaling Constants (Weights) for Each Attribute Are:

INITIAL COST IMPCT:	0.5000
OPERATIONS COSTS:	0.7000
CREW PRODUCTIVITY:	0.6500
SAFETY:	0.5500
DEVELOPMENT RISK:	0.4500
RESOURCE REQTS IMP:	0.3500
GROWTH POTENTIAL:	0.6000
SPINOFF POTENTIAL:	0.2500

The Utility Functions for Each Attribute Are:

ATTRIBUTE: INITIAL COST IMPCT

State	Utility	State	Utility	State	Utility
0.0000	0.00	5.0000	0.50	10.0000	1.00

ATTRIBUTE: OPERATIONS COSTS

State	Utility	State	Utility	State	Utility
0.0000	0.00	4.0000	0.50	10.0000	1.00

ATTRIBUTE: CREW PRODUCTIVITY

State	Utility	State	Utility	State	Utility
0.0000	0.00	4.0000	0.50	10.0000	1.00

ATTRIBUTE: SAFETY

State	Utility	State	Utility	State	Utility
0.0000	0.00	4.0000	0.50	10.0000	1.00

ATTRIBUTE: DEVELOPMENT RISK

State	Utility	State	Utility	State	Utility
0.0000	0.00	5.0000	0.50	10.0000	1.00

ATTRIBUTE: RESOURCE REQTS IMP

State	Utility	State	Utility	State	Utility
0.0000	0.00	5.0000	0.50	10.0000	1.00

ATTRIBUTE: GROWTH POTENTIAL

State	Utility	State	Utility	State	Utility
0.0000	0.00	6.0000	0.50	10.0000	1.00

ATTRIBUTE: SPINOFF POTENTIAL

State	Utility	State	Utility	State	Utility
0.0000	0.00	4.0000	0.50	10.0000	1.00

Attribute Preferences for Individual: INTRVW 02

Scaling Constants (Weights) for Each Attribute Are:

INITIAL COST IMPCT:	0.5000
OPERATIONS COSTS:	0.3500
CREW PRODUCTIVITY:	0.3000
SAFETY:	0.5000
DEVELOPMENT RISK:	0.0500
RESOURCE REQTS IMP:	0.3000
GROWTH POTENTIAL:	0.0500
SPINOFF POTENTIAL:	0.0500

The Utility Functions for Each Attribute Are:

ATTRIBUTE: INITIAL COST IMPCT

State	Utility	State	Utility	State	Utility
0.0000	0.00	5.5000	0.50	10.0000	1.00

ATTRIBUTE: OPERATIONS COSTS

State	Utility	State	Utility	State	Utility
0.0000	0.00	3.5000	0.50	10.0000	1.00

ATTRIBUTE: CREW PRODUCTIVITY

State	Utility	State	Utility	State	Utility
0.0000	0.00	2.5000	0.50	10.0000	1.00

ATTRIBUTE: SAFETY

State	Utility	State	Utility	State	Utility
0.0000	0.00	5.5000	0.50	10.0000	1.00

ATTRIBUTE: DEVELOPMENT RISK

State	Utility	State	Utility	State	Utility
0.0000	0.00	8.0000	0.50	10.0000	1.00

ATTRIBUTE: RESOURCE REQTS IMP

State	Utility	State	Utility	State	Utility
0.0000	0.00	2.5000	0.50	10.0000	1.00

ATTRIBUTE: GROWTH POTENTIAL

State	Utility	State	Utility	State	Utility
0.0000	0.00	6.5000	0.50	10.0000	1.00

ATTRIBUTE: SPINOFF POTENTIAL

State	Utility	State	Utility	State	Utility
0.0000	0.00	9.5000	0.50	10.0000	1.00

Attribute Preferences for Individual: INTRVW 03

Scaling Constants (Weights) for Each Attribute Are:

INITIAL COST IMPCT:	0.2500
OPERATIONS COSTS:	0.3000
CREW PRODUCTIVITY:	0.5000
SAFETY:	0.4000
DEVELOPMENT RISK:	0.2500
RESOURCE REQTS IMP:	0.2500
GROWTH POTENTIAL:	0.2500
SPINOFF POTENTIAL:	0.2500

The Utility Functions for Each Attribute Are:

ATTRIBUTE: INITIAL COST IMPCT

State	Utility	State	Utility	State	Utility
0.0000	0.00	5.0000	0.50	10.0000	1.00

ATTRIBUTE: OPERATIONS COSTS

State	Utility	State	Utility	State	Utility
0.0000	0.00	2.5000	0.50	10.0000	1.00

ATTRIBUTE: CREW PRODUCTIVITY

State	Utility	State	Utility	State	Utility
0.0000	0.00	8.0000	0.50	10.0000	1.00

ATTRIBUTE: SAFETY

State	Utility	State	Utility	State	Utility
0.0000	0.00	8.0000	0.50	10.0000	1.00

ATTRIBUTE: DEVELOPMENT RISK

State	Utility	State	Utility	State	Utility
0.0000	0.00	5.0000	0.50	10.0000	1.00

ATTRIBUTE: RESOURCE REQTS IMP

State	Utility	State	Utility	State	Utility
0.0000	0.00	5.0000	0.50	10.0000	1.00

ATTRIBUTE: GROWTH POTENTIAL

State	Utility	State	Utility	State	Utility
0.0000	0.00	5.0000	0.50	10.0000	1.00

ATTRIBUTE: SPINOFF POTENTIAL

State	Utility	State	Utility	State	Utility
0.0000	0.00	5.0000	0.50	10.0000	1.00

Attribute Preferences for Individual: INTRVW 04

Scaling Constants (Weights) for Each Attribute Are:

INITIAL COST IMPCT:	0.4000
OPERATIONS COSTS:	0.7000
CREW PRODUCTIVITY:	0.7000
SAFETY:	0.5000
DEVELOPMENT RISK:	0.5500
RESOURCE REQTS IMP:	0.5500
GROWTH POTENTIAL:	0.4000
SPINOFF POTENTIAL:	0.2500

The Utility Functions for Each Attribute Are:

ATTRIBUTE: INITIAL COST IMPCT

State	Utility	State	Utility	State	Utility
0.0000	0.00	4.5000	0.50	10.0000	1.00

ATTRIBUTE: OPERATIONS COSTS

State	Utility	State	Utility	State	Utility
0.0000	0.00	4.5000	0.50	10.0000	1.00

ATTRIBUTE: CREW PRODUCTIVITY

State	Utility	State	Utility	State	Utility
0.0000	0.00	4.0000	0.50	10.0000	1.00

ATTRIBUTE: SAFETY

State	Utility	State	Utility	State	Utility
0.0000	0.00	3.5000	0.50	10.0000	1.00

ATTRIBUTE: DEVELOPMENT RISK

State	Utility	State	Utility	State	Utility
0.0000	0.00	5.5000	0.50	10.0000	1.00

ATTRIBUTE: RESOURCE REQTS IMP

State	Utility	State	Utility	State	Utility
0.0000	0.00	4.5000	0.50	10.0000	1.00

ATTRIBUTE: GROWTH POTENTIAL

State	Utility	State	Utility	State	Utility
0.0000	0.00	6.0000	0.50	10.0000	1.00

ATTRIBUTE: SPINOFF POTENTIAL

State	Utility	State	Utility	State	Utility
0.0000	0.00	2.0000	0.50	10.0000	1.00

Attribute Preferences for Individual: INTRVW 05

Scaling Constants (Weights) for Each Attribute Are:

INITIAL COST IMPCT:	0.6500
OPERATIONS COSTS:	0.6500
CREW PRODUCTIVITY:	0.6500
SAFETY:	0.2000
DEVELOPMENT RISK:	0.5000
RESOURCE REQTS IMP:	0.5000
GROWTH POTENTIAL:	0.6000
SPINOFF POTENTIAL:	0.4000

The Utility Functions for Each Attribute Are:

ATTRIBUTE: INITIAL COST IMPCT

State	Utility	State	Utility	State	Utility
0.0000	0.00	6.2980	0.50	10.0000	1.00

ATTRIBUTE: OPERATIONS COSTS

State	Utility	State	Utility	State	Utility
0.0000	0.00	3.0000	0.50	10.0000	1.00

ATTRIBUTE: CREW PRODUCTIVITY

State	Utility	State	Utility	State	Utility
0.0000	0.00	4.5000	0.50	10.0000	1.00

ATTRIBUTE: SAFETY

State	Utility	State	Utility	State	Utility
0.0000	0.00	4.0000	0.50	10.0000	1.00

ATTRIBUTE: DEVELOPMENT RISK

State	Utility	State	Utility	State	Utility
0.0000	0.00	4.7980	0.50	10.0000	1.00

ATTRIBUTE: RESOURCE REQTS IMP

State	Utility	State	Utility	State	Utility
0.0000	0.00	3.0000	0.50	10.0000	1.00

ATTRIBUTE: GROWTH POTENTIAL

State	Utility	State	Utility	State	Utility
0.0000	0.00	6.0000	0.50	10.0000	1.00

ATTRIBUTE: SPINOFF POTENTIAL

State	Utility	State	Utility	State	Utility
0.0000	0.00	5.5000	0.50	10.0000	1.00

Attribute Preferences for Individual: INTRVW 06

Scaling Constants (Weights) for Each Attribute Are:

INITIAL COST IMPCT:	0.5000
OPERATIONS COSTS:	0.7500
CREW PRODUCTIVITY:	0.7200
SAFETY:	0.7500
DEVELOPMENT RISK:	0.5500
RESOURCE REQTS IMP:	0.4500
GROWTH POTENTIAL:	0.5500
SPINOFF POTENTIAL:	0.4000

The Utility Functions for Each Attribute Are:

ATTRIBUTE: INITIAL COST IMPCT

State	Utility	State	Utility	State	Utility
0.0000	0.00	6.5000	0.50	10.0000	1.00

ATTRIBUTE: OPERATIONS COSTS

State	Utility	State	Utility	State	Utility
0.0000	0.00	7.5000	0.50	10.0000	1.00

ATTRIBUTE: CREW PRODUCTIVITY

State	Utility	State	Utility	State	Utility
0.0000	0.00	5.0000	0.50	10.0000	1.00

ATTRIBUTE: SAFETY

State	Utility	State	Utility	State	Utility
0.0000	0.00	5.0000	0.50	10.0000	1.00

ATTRIBUTE: DEVELOPMENT RISK

State	Utility	State	Utility	State	Utility
0.0000	0.00	4.0000	0.50	10.0000	1.00

ATTRIBUTE: RESOURCE REQTS IMP

State	Utility	State	Utility	State	Utility
0.0000	0.00	6.5000	0.50	10.0000	1.00

ATTRIBUTE: GROWTH POTENTIAL

State	Utility	State	Utility	State	Utility
0.0000	0.00	6.0000	0.50	10.0000	1.00

ATTRIBUTE: SPINOFF POTENTIAL

State	Utility	State	Utility	State	Utility
0.0000	0.00	5.5000	0.50	10.0000	1.00

Attribute Preferences for Individual: INTRVW 07

Scaling Constants (Weights) for Each Attribute Are:

INITIAL COST IMPCT:	0.3000
OPERATIONS COSTS:	0.2000
CREW PRODUCTIVITY:	0.3000
SAFETY:	0.2000
DEVELOPMENT RISK:	0.3000
RESOURCE REQTS IMP:	0.2000
GROWTH POTENTIAL:	0.3000
SPINOFF POTENTIAL:	0.1000

The Utility Functions for Each Attribute Are:

ATTRIBUTE: INITIAL COST IMPCT

State	Utility	State	Utility	State	Utility
0.0000	0.00	4.0000	0.50	10.0000	1.00

ATTRIBUTE: OPERATIONS COSTS

State	Utility	State	Utility	State	Utility
0.0000	0.00	3.0000	0.50	10.0000	1.00

ATTRIBUTE: CREW PRODUCTIVITY

State	Utility	State	Utility	State	Utility
0.0000	0.00	7.0000	0.50	10.0000	1.00

ATTRIBUTE: SAFETY

State	Utility	State	Utility	State	Utility
0.0000	0.00	6.0000	0.50	10.0000	1.00

ATTRIBUTE: DEVELOPMENT RISK

State	Utility	State	Utility	State	Utility
0.0000	0.00	5.0000	0.50	10.0000	1.00

ATTRIBUTE: RESOURCE REQTS IMP

State	Utility	State	Utility	State	Utility
0.0000	0.00	4.0000	0.50	10.0000	1.00

ATTRIBUTE: GROWTH POTENTIAL

State	Utility	State	Utility	State	Utility
0.0000	0.00	7.0000	0.50	10.0000	1.00

ATTRIBUTE: SPINOFF POTENTIAL

State	Utility	State	Utility	State	Utility
0.0000	0.00	3.0000	0.50	10.0000	1.00

Attribute Preferences for Individual: INTRVW 08

Scaling Constants (Weights) for Each Attribute Are:

INITIAL COST IMPCT:	0.5500
OPERATIONS COSTS:	0.5500
CREW PRODUCTIVITY:	0.4500
SAFETY:	0.4500
DEVELOPMENT RISK:	0.4500
RESOURCE REQTS IMP:	0.4500
GROWTH POTENTIAL:	0.4000
SPINOFF POTENTIAL:	0.3000

The Utility Functions for Each Attribute Are:

ATTRIBUTE: INITIAL COST IMPCT

State	Utility	State	Utility	State	Utility
0.0000	0.00	5.0000	0.50	10.0000	1.00

ATTRIBUTE: OPERATIONS COSTS

State	Utility	State	Utility	State	Utility
0.0000	0.00	3.5000	0.50	10.0000	1.00

ATTRIBUTE: CREW PRODUCTIVITY

State	Utility	State	Utility	State	Utility
0.0000	0.00	5.0000	0.50	10.0000	1.00

ATTRIBUTE: SAFETY

State	Utility	State	Utility	State	Utility
0.0000	0.00	4.0000	0.50	10.0000	1.00

ATTRIBUTE: DEVELOPMENT RISK

State	Utility	State	Utility	State	Utility
0.0000	0.00	5.0000	0.50	10.0000	1.00

ATTRIBUTE: RESOURCE REQTS IMP

State	Utility	State	Utility	State	Utility
0.0000	0.00	3.5000	0.50	10.0000	1.00

ATTRIBUTE: GROWTH POTENTIAL

State	Utility	State	Utility	State	Utility
0.0000	0.00	5.0000	0.50	10.0000	1.00

ATTRIBUTE: SPINOFF POTENTIAL

State	Utility	State	Utility	State	Utility
0.0000	0.00	5.0000	0.50	10.0000	1.00

Attribute Preferences for Individual: INTRVW 09

Scaling Constants (Weights) for Each Attribute Are:

INITIAL COST IMPCT:	0.7000
OPERATIONS COSTS:	0.7000
CREW PRODUCTIVITY:	0.6000
SAFETY:	0.6000
DEVELOPMENT RISK:	0.5000
RESOURCE REQTS IMP:	0.6000
GROWTH POTENTIAL:	0.5000
SPINOFF POTENTIAL:	0.5000

The Utility Functions for Each Attribute Are:

ATTRIBUTE: INITIAL COST IMPCT

State	Utility	State	Utility	State	Utility
0.0000	0.00	7.0000	0.50	10.0000	1.00

ATTRIBUTE: OPERATIONS COSTS

State	Utility	State	Utility	State	Utility
0.0000	0.00	6.0000	0.50	10.0000	1.00

ATTRIBUTE: CREW PRODUCTIVITY

State	Utility	State	Utility	State	Utility
0.0000	0.00	6.0000	0.50	10.0000	1.00

ATTRIBUTE: SAFETY

State	Utility	State	Utility	State	Utility
0.0000	0.00	5.0000	0.50	10.0000	1.00

ATTRIBUTE: DEVELOPMENT RISK

State	Utility	State	Utility	State	Utility
0.0000	0.00	5.0000	0.50	10.0000	1.00

ATTRIBUTE: RESOURCE REQTS IMP

State	Utility	State	Utility	State	Utility
0.0000	0.00	5.0000	0.50	10.0000	1.00

ATTRIBUTE: GROWTH POTENTIAL

State	Utility	State	Utility	State	Utility
0.0000	0.00	5.0000	0.50	10.0000	1.00

ATTRIBUTE: SPINOFF POTENTIAL

State	Utility	State	Utility	State	Utility
0.0000	0.00	5.0000	0.50	10.0000	1.00

APPENDIX D

POST-PROCESS QUESTIONNAIRE

Jet Propulsion Laboratory
California Institute of Technology

4800 Oak Grove Drive
Pasadena, California 91109

(818) 354-4321

JPL

August 10, 1989

Dear Colleague:

Recently you participated in an evaluation of the Automation and Robotics (A&R) proposals which had been submitted as candidates for high leverage (moderate-to-high risk, high payoff) A&R prototyping. Enclosure 2 summarizes the results of that activity. Background materials are enclosed together with the results of the ranking as Enclosure 3. This package was assembled to inform you of the results and thank you for your participation.

We are interested in your complete and candid evaluation of the entire process, from initial proposal submissions to final ranking. Enclosure 1 was prepared to obtain those evaluations. Your evaluations will assist us in exposing any weaknesses in the process. They will also permit us to improve the process by modifying our questionnaires, interviews, etc., to circumvent such problems. Either signed or anonymous questionnaires can be returned. No individual responses will be quoted or identified. Only overall results and summaries will be used in reporting back to the Space Station Program Office.

Three categories of participants were involved (technical assessors, decision makers [interviewees], and interested observers). Please identify your participation category and respond as completely as possible to the questions. The questionnaire is divided into three sections. Section A explores your overall reaction to the evaluation process. Section B refers to the technical assessment. Section C applies to the prioritization process.

Completed questionnaires should be returned by August 30, 1989. An addressed envelope is provided for your convenience. Reston participants can return the questionnaire to Ms. E. Carpenter (SSR). If you did not attend the June briefing and have a question, please contact me at tel. (818) 354-1236 (FTS 792-1236). Once again, thank you for your participation.

Dr. Jeffrey H. Smith

Enclosures

Appendix D: Post-Process Questionnaire

A&R PROPOSAL EVALUATION QUESTIONNAIRE

10 August, 1989

Please complete the following by checking the appropriate box (NA indicates "no answer"; e.g., not familiar with topic)

I participated in the evaluation as a:

☐ Technical assessor (attribute ratings) ☐ Decision maker (prioritized the attributes) ☐ Interested Observer

A. YOUR OVERALL REACTION TO THE EVALUATION	Unsatisfactory	Poor	Fair	Good	Excellent	NA
(1) Describe the value of ranking the A&R candidates in improving your understanding of them.	☐	☐	☐	☐	☐	☐
(2) Describe the value of rankings for evaluating A&R candidates.	☐	☐	☐	☐	☐	☐
(3) Describe the usefulness of the results for measuring candidate value.	☐	☐	☐	☐	☐	☐
(4) Describe the effectiveness of the safeguards in preventing "gaming" by the participants.	☐	☐	☐	☐	☐	☐
(5) Describe the fairness of the process from the proposers' point of view.	☐	☐	☐	☐	☐	☐
(6) Describe the fairness of the process from your point of view.	☐	☐	☐	☐	☐	☐
(7) Describe the efficiency of the process for generating final rankings	☐	☐	☐	☐	☐	☐
(8) After examining the results, describe your intuitive concurrence.	☐	☐	☐	☐	☐	☐
(9) Describe the utility to you of similar processes in future evaluations.	☐	☐	☐	☐	☐	☐
B. THE TECHNICAL ASSESSMENT PROCESS						
(1) Describe the reasonableness of the groundrules.	☐	☐	☐	☐	☐	☐
(2) Describe the adequacy of the process in addressing the uncertainties in candidate attributes.	☐	☐	☐	☐	☐	☐
(3) Describe the validity of using arguments for and against the attribute ratings in establishing technical credibility.	☐	☐	☐	☐	☐	☐
(4) Describe the credibility of the technical assessment process.	☐	☐	☐	☐	☐	☐
(5) Describe the adequacy of the technical assessment process in preventing "gaming."	☐	☐	☐	☐	☐	☐
C. THE ASSESSMENT OF PRIORITIES						
(1) Describe the adequacy of *SSF* Decision Maker representation, given the scope of the evaluation.	☐	☐	☐	☐	☐	☐
(2) Describe the utility of the group decision rules for expressing group preferences.	☐	☐	☐	☐	☐	☐

(3) If asked to participate in a future evaluation, would you prefer a process with:

☐ Analyst support only? ☐ Interactive computer support with analyst backup? ☐ Stand-alone computer software with analyst coordination?

ADDITIONAL COMMENTS: